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A REPRESENTATIVE SURVEY OF U.S. SPACE SYSTEMS AND METHODS FOR ESTIMATING THEIR COSTS

J. Richard Nelson, *Project Leader*
James Bui
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Jennifer A. Titus
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November 1992

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The purpose of this project was to expand and enhance IDA's capabilities to estimate the future acquisition costs and schedules of space systems. Prior to this study, data and methods were available only for unmanned earth-orbiting space systems. These data were obtained from the Department of Defense. This study accumulated information on launch systems, manned space systems, and interplanetary systems from NASA. Cost and schedule information was collected on representative programs, estimating methods, and supporting databases. Sources included NASA Headquarters and the centers that routinely do cost-estimating work. The results of the effort include this document, which summarizes costs and schedules of representative space systems along with cost-estimating methods currently being applied, and also a library of over 500 documents that describe technical, schedule, and cost characteristics of U.S. space activities during the past 40 years. Preliminary findings of this study have been applied to estimate the costs of manned access to space. These findings provide a foundation for estimates of the costs and schedules of space systems addressed in future IDA studies.

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PREFACE

This document was prepared by the Institute for Defense Analyses (IDA) under the IDA Independent Research Program. The objective of the task was to assemble an open-literature database to support cost and historical research on selected elements of the U.S. space program.

This document was reviewed within IDA by Joseph W. Stahl and William J. E. Shafer.

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TABLES

I. INTRODUCTION

This Central Research Project (CRP) was conducted to expand and enhance IDA's capabilities to estimate the future acquisition costs and schedules of space systems. Prior to this effort, IDA provided estimates of costs and schedules of unmanned earth-orbiting space systems to the Strategic Defense Initiative Organization (SDIO) and the Defense Information Systems Agency (DISA). This CRP expanded IDA's perspective to include launch systems, manned space systems, and interplanetary systems. We collected information on representative programs, estimating methods, and supporting databases for all types of U.S. space systems, including instruments and payloads that fly on these systems.

The following work was accomplished during the course of this CRP:

- An extensive literature search was completed and a CARD library was established of over 500 space-related documents pertaining to technical, schedule, and cost data on NASA and U.S. space activities during the past 40 years.
- Contacts were established at NASA Headquarters and at selected NASA Centers that do cost and schedule estimating work.
- The current methods being used by NASA personnel responsible for estimating costs for selected types of systems were reviewed.
- Appropriate NASA databases and methods were obtained for internal IDA use.

This document describes the methods and databases available from NASA sources, and presents the technical, schedule and cost information that has been collected on a variety of space systems. The systems are divided into four categories: manned spacecraft (Chapter II), launch vehicles (Chapter III), unmanned spacecraft (Chapter IV), and instruments (Chapter V). Each chapter opens with a description of the cost-estimating methods for that category of space system. This is followed by detailed descriptions of various programs that are representative of systems in the particular category. Interspersed among the program descriptions are tables showing the chronology, characteristics, and funding for each of the programs for which the information was available in a non-proprietary form. We have tried to present comparable data across systems.

Appendix A provides inflation indices used throughout the report to convert then-year costs to 1990 dollars. Appendix B contains a chronicle of U.S. unmanned spacecraft by category.

This CRP was concerned with existing methods and databases only. The information was intended to serve as a baseline for estimating program costs for the types of systems described. No attempt has been made to develop new methods or databases.

II. MANNED SPACECRAFT

A. COST MODELS

We examined three manned spacecraft cost models: the NASA Cost Model (Planning Research Corporation 1990a), Cost Estimating Methods for Advanced Space Systems developed at the Johnson Space Center (Cyr 1988), and Manned Spacecraft Cost-Estimating Relationships developed by the RAND Corporation (Campbell and Dreyfuss 1967).

1. NASA Cost Model

The NASA Cost Model (NASCOM), developed by the Planning Research Corporation (PRC), is based on the NASCOM database (NASCOM-DB), as extracted from the REDSTAR database. The manned section of NASCOM-DB contains the following seven manned spacecraft:

- Apollo Command Service Module
- Apollo Lunar Module
- Gemini
- Skylab Airlock
- Skylab Orbital Workshop
- Spacelab
- Shuttle Orbiter.

Each of the parametric equations in NASCOM are weight-driven. NASCOM cost-estimating relationships (CERs) are based on First Pound Costs that incorporate the spacecraft's weight, and factors to adjust for weight contingency, weight uniqueness, new design, complexity, and specification level. NASCOM contains three separate cost-estimating methods.

Method one is a set of spacecraft-level CERs that are useful for quick estimations. NASCOM provides a Design, Development, Test and Evaluation (DDT&E) equation and a First Unit Cost (T1) equation. The CERs were developed with assumed slopes of 0.5 for

DDT&E and 0.7 for the T1. These slopes were derived from previous cost models. The CERs use the equation form $y = ax^b$, where y is the cost in 1989 dollars, x is the dry weight, b is the assumed slope, and a is the first pound cost. The first pound costs are provided.

Method two is a set of subsystem CERs. The equation $y = ax^b$ is again used for these CERs. The subsystem first pound costs, component first pound costs, and slopes are provided for the DDT&E and T1 equations.

Method three is an analogous technique. Component- and subsystem-level contractor costs are provided for the same seven manned spacecraft. The estimator chooses the spacecraft that most closely matches the specifications of the spacecraft being estimated and uses the first pound cost coefficients for the DDT&E and T1 costs.

2. Johnson Space Center Model

The Johnson Space Center (JSC) model is a parametric cost-estimating model for space systems in the conceptual design phase. It is a long-range forecasting tool based on a database of 264 major programs. The major categories within the database include ground vehicles, ships, aircraft, missiles, and spacecraft.

The CER provided is based on variables that drive cost, such as weight, quantity, development culture, design inheritance, and time. The equation is the result of multiple linear regression analysis:

$$\text{Cost} = 0.0000172Q^{0.5773}\, W^{0.6569}\, 58.95^{C}\, 1.0291^{Y}\, G^{-0.3485},$$

where $Q = \log_{10}$ total quantity, $W = \log_{10}$ weight, C = culture, Y = initial operational capability year, and G = generation. Culture is a derived variable based on functionally similar hardware groups.

3. Manned Spacecraft Cost-Estimating Relationships

Manned Spacecraft Cost-Estimating Relationships was prepared for NASA in March of 1967. The model provides three functional CERs for sixteen manned spacecraft subsystems. The three functional CERs analyze engineering hours, developmental support costs, and production costs. Ground support equipment, training, launch support, and spares are dealt with at the spacecraft level.

The model is based on data from the Mercury, Gemini, and Apollo programs. The CERs were not the result of regression analysis, because so few data points were available.

The data was analyzed in a more subjective manner. First, possible physical or performance subsystem cost drivers were determined. Next, those drivers were plotted against the costs, and the resulting equation was analyzed.

The engineering hours and production cost CERs generally take the form:

$$C = a(\text{subsystem weight})^{b}.$$

The development support costs CERs take the form:

$$C = a(\text{engineering hours})^{b},$$

where a and b are provided. The reaction control, earth landing system, and space propulsion subsystem CERs are based on total impulse and reentry module weight.

B. PROGRAMS

1. Mercury

Project Mercury was NASA's first manned space flight effort. Its three main goals were to launch a manned spacecraft into earth orbit to recover the pilot and the spacecraft, and to assess man's capability for space flight and to function in space.

The program lasted about five years altogether, commencing with the October 1958 decision to proceed by the NASA administrator. In January 1958, NASA selected McDonnell Aircraft Company to be the spacecraft prime contractor. The first full-up production spacecraft was delivered in April 1960. John Glenn's successful mission less than two years later in February 1962, achieved the program's main goal of manned earth orbit.

The program was characterized by reliance on existing technology and off-the-shelf equipment, when practical, and pursuing the simplest, most reliable approach to system design (Ezell 1988). Existing Redstone and Atlas ballistic missiles were used throughout the test and operational flight program.

The program was not without notable engineering achievements. These included the Mercury capsule's ablative heatshield, the design concepts for reentry and recovery of the capsule, the development of an automatic escape system for the Redstone and Atlas boosters, and the construction of the world-wide tracking network. Advances were also made in fabrication of structures with materials that were advanced for the time.

The program was not without problems. In particular, early reliability analyses had suggested that the booster would be the principal reliability driver. Yet the Atlas missile, the prime mover for the Mercury capsule for orbital missions, was a relatively recent development. Flight testing of the Atlas had started in June 1957, and the missile only achieved its design range in November 1958.

Table 1. Project Mercury Chronology

Milestone	Date	Source	Notes
Pre-project go-ahead R&D start	3/58	a	
Project Start/go ahead	10/58	b	Program approval by NASA; project initiated
Request for proposals	11/58	b	Bidder's briefing; spacecraft specifications sent out 10/58
Source selection	1/59	b	McDonnell Aircraft
Contract start (authority to proceed)	2/59	b	McDonnell Aircraft for Mercury capsule
	12/58	b	North American for Little Joe test program booster
First drawing release	2/59	a	
95% structural drawing release	6/59	a	
Design freeze	5/59	a	
First delivery	1/60	b	s/c #4; originally contracted for 9/59
Start flight test	8/59	1	LJ-1; boilerplate spacecraft; originally scheduled for 7/59
First launch prime spacecraft	5/60	b	Beach abort mission; s/c #1
First flight prime spacecraft	7/60	b	MA-1; Mercury/Atlas configuration qualification; originally scheduled for 7/59
First ballistic/orbital flight prime spacecraft	12/60	b	MR-1A, MR1 originally scheduled for 10/59
First manned flight	5/61	b	MR-3; originally scheduled for 1/60
End unmanned flight test program	11/61	b	MA-5; orbital test of environmental control system; primate crew; originally scheduled for 3/60
Last manned flight completion	5/63	b	MA-9 originally scheduled for 8/60

[a] Vought Missile Systems Corporation (1972).

[b] Grimwood (1983) and Swenson, Grimwood, and Alexander (1966).

The Air Force developers had also expected that adapting the Atlas to the Mercury payload would not be difficult. Swenson, Grimwood, and Alexander (1966) write in their history of the Mercury program, "Once the Abort Sensing and Implementation System was proven and installed, the Atlas ICBM should, it was hoped, be electromechanically transformed into the Mercury-Atlas launch vehicle."

Table 2. Mercury Spacecraft Characteristics

Characteristic	Measurement	Source
Shape	Conical, 2.1m wide at base, 3.4 m long	a
Planform area	3.92 m^2	c
Habitable volume	1.02 m^3	a
Dry weight	1362 kg	b
Empty weight	1574 kg	c
Structure Weight	503 kg	c
Gross weight	1855 kg	c
Reentry weight	1208 kg	a
Systems weight	1072 kg	c
Useful load	280 kg	c
Maximum design temperature	1371° F	c

[a] NASA, Project Mercury Quarterly Status Reports.
[b] Campbell and Dreyfus (1967).
[a] Vought Missile Systems Corporation (1972).

Table 3. Project Mercury Expenditures, FY 1959-63

Function	Expenditures (millions of constant 1990 dollars)				
	FY 1959	FY 1960	FY 1961	FY 1962	FY 1963
Tracking and data acquisition, integrated system, study and test			2.33		
Tracking and data acquisition, network operations		0.40	0.17		
Spacecraft	105.31	386.36	252.96	4.67	
Scout	24.69				
Atlas	65.53	69.22	139.82	31.08	
Little Joe	15.99	0.07	0.18		
Redstone	56.31	11.94	12.21		
Jupiter	11.17				
Big Joe	2.74	0.08			
Spacecraft support	8.95	14.96	11.86	1.88	
Flight operations				6.40	0.16
Recovery operations			14.54	32.67	0.42
Network operations			50.18		
Network implementation			73.12		
General administrative expense	0.24	0.58	2.50	30.57	
Program overhead	0.72	1.79	6.39	10.51	1.46
Salaries and expenses	8.36	30.11	45.20	49.01	
Equipment and instrumentation		3.01			

Source: Grimwood (1983).
Note: Table A-1 in Appendix A provides the deflators used.

Manrating the missile proved to be more difficult than expected. For instance, the catastrophic failure of the first Mercury-Atlas flight (MA-1) led to structural reinforcement of the launch vehicle airframe for the Mercury mission. Ultimately, a manrated Mercury-Atlas may have cost up to forty percent more to develop than an Atlas ICBM (Swenson, Grimwood, and Alexander 1966, p. 189).

As a result of accumulating delays, Alan Shepard made the program's first manned flight sixteen months later than originally scheduled; John Glenn achieved earth orbital flight, the program's principal goal, thirteen months later than originally scheduled. However, as the development program progressed and engineers solved hardware reliability problems, the early test failures were followed by successes for the remainder of the program, including all six manned flights. The success of the manned, operational part of the program was such that NASA canceled MA-10, the very last planned Mercury flight, in June 1963.

Proprietary Project Mercury development costs are exhibited in Campbell and Dreyfus (1967).

2. Gemini

Project Gemini was the advanced follow-on to the Mercury program and the testbed for concepts important to the Apollo program. Its origins are well-summarized by Hacker and Grimwood (1977, pp. xv-xvi) in their history of the program.

> President John F. Kennedy's decision in May 1961 to commit the United States to landing on the Moon before the end of the decade gave Gemini its central objective. NASA planners had been thinking about the Moon, an obvious goal for manned space flight, almost from the moment the agency itself was created in 1958. The Moon, however, was seen as a target for the 1970s, pending development of a huge rocket, called Nova. It would launch a spacecraft that would fly directly to the Moon, land there, and then return. This direct approach was widely accepted on the grounds that it was almost certain to work.
>
> Some NASA engineers had advocated an alternative method, in which two or more spacecraft rendezvous in orbit rather than proceed directly to the Moon. This approach promised enormous savings in fuel and weight; the lunar mission based on rendezvous might be launched with smaller rockets. The greatest drawback of this approach was its novelty. No one knows how hard a rendezvous in space might be. So long as time was ample, the direct method offered by far the safer prospect. When the President imposed a deadline, however, support for rendezvous waxed. It promised a quicker and cheaper road to the Moon if it could be achieved. The "if" was a big one in 1961, big enough to justify

> the expense of a full-fledged manned space flight project to resolve it. Gemini was first and foremost a project to develop and prove equipment and techniques for rendezvous.
>
> That the project turned out to be Gemini, however, rather than something else, resulted from a second distinct chain of causes. Government and industry engineers who worked in Project Mercury saw innumerable ways to improve their product. Gemini's second taproot was an engineering concern to improve spacecraft technology beyond the first step that was Mercury.

The project had other goals as well: observing the effects of long-duration stays in space; evaluating the concept of a controlled landing; training flight and ground crew; and performing various experiments, including extra-vehicular activities.

Perhaps due to its peculiar position as a bridge from Mercury to Apollo, time and schedule were central historical elements of the Gemini program. As an advanced follow-on to Mercury, NASA and McDonnell Aircraft engineers had been studying modifications to the Mercury design even before Allan Shepard's first manned Mercury flight. However, as an intermediate step to Apollo, Gemini was bound by severe time constraints, such that it could not, whatever happened, be allowed to overlap or interfere with Project Apollo. As a result, by the time the project formally commenced, much of the design work had been done and many of the major policy decisions had already been made.

In December 1961, just a week after project approval, NASA gave McDonnell Aircraft an uncompeted contract to produce the so-called Mercury Mark II spacecraft.

Those redesigning the Mercury capsule, even before the Gemini program had taken space, strove for simplification and improved accessibility, serviceability, and reliability in the modified spacecraft. The modification was to focus on the internal structure of the Mercury capsule, its external configuration to be largely preserved in the new spacecraft. However, the evolving mission profiles for a Mercury follow-on, i.e., longer duration and extravehicular activity, demanded a larger spacecraft to accommodate a second crewmember, more consumables, and onboard experiments, in addition to provisions for rendezvous and docking operations.

Other significant goals for a redesigned mercury capsule included: (1) internal capsule reconfiguration to expedite checkout and maintenance through equipment relocation, i.e., outside the cabin for improved access, and modular design; and (2) development of a paraglider system for controlled reentry of the capsule. This goal was abandoned because development problems conflicted with the aforementioned schedule constraints.

Table 4. Project Gemini Chronology

Milestone	Date	Source	Notes
Pre-project go-ahead R&D start	4/61	a	McDonnell Aircraft, Mercury Improvement Study contract
Project Start/go ahead	8/61	b	STG preliminary plan
	12/61	a	Approval of Mercury Mark II plan
Source selection	12/61	a	Noncompetitive choice of McDonnell Aircraft
Contract start (authority to proceed)	12/61	a	Letter contract
Mockup started	1/62	a	
Mockup complete	11/62	a	Following mockup review of 8/62
95% structural drawing release	9/62	b	
Design freeze	3/62	a	
First production delivery	10/63	a	Originally scheduled for 10/63
Start flight test	4/64	a	GT-1; originally scheduled for 7/63
First manned flight	3/65	a	GT-3; originally scheduled for 11/63
End unmanned flight test program	1/65	a	
Last manned flight completion	11/66	a	

[a] Grimwood, Hacker, and Vorzimmer (1969); Hacker and Grimwood (1977); and NASA, Project Gemini Quarterly Status Reports.

[b] Vought Missile Systems Corporation (1972).

Table 5. Gemini Spacecraft Characteristics

Characteristic	Measurement	Source
Shape	conical, 3.05m wide at base, 5.74m long	a
Planform area	8.27 m^2	c
Habitable volume	1.56 m^3	a
Dry weight	2593 kg	b
Empty weight	2832 kg	c
Structure Weight	1056 kg	c
Gross weight	3856 kg	c
Reentry weight	2165 kg	a
Systems weight	1776 kg	c
Useful load	1024 kg	c
Maximum design temperature	1371° F	c

[a] Ezell (1988, vol. II).

[b] Campbell (1967).

[c] Vought Missile Systems Corporation (1972).

Also new to the Gemini program was the Air Force's Titan II launch vehicle, which was still in development by the Air Force at the start of the program, and its Agena second

stage, to be used as the Gemini target vehicle. Both programs severely complicated the course of the Gemini program.

At the outset of its test program, the Titan II launch vehicle experienced multi-g longitudinal vibration, then termed "pogo," which posed serious problems throughout most of 1963. Insufficient thrust and combustion instability in the second stage also posed significant problems for the launch vehicle. The Agena and the Gemini spacecraft's propulsion systems were developmentally difficult systems, as was its orbital attitude and maneuvering system, which was the source of continuing problems throughout the operational stage of the program.

Also of note were significant development problems with Gemini spacecraft's fuel cell, escape system, thrusters, and the new paraglider landing system. However, the resolution of these problems were at least within sight in 1964 for all but paraglider development, which ceased that year.

Of at least equal concern as the technical challenges to the Gemini program were the budgetary problems. Program managers labored under a severe financial crisis during its first year, as well as lesser such crises throughout its life. According to Hacker and Grimwood (1977, p. xvii): "More than once, lack of funds threatened the loss of one or another of its major goals, and money problems played a key role in managerial changes in 1963."

The Gemini program formally commenced in December 1961 and achieved a first unmanned test flight in April 1964, 8 months later than the August 1963 date scheduled before the budget crisis of 1962, and 4 months behind the December 1963 date resulting from its resolution. The first manned Gemini flight took place a year later in March 1965, 16 months later than scheduled before the 1962 budget crisis and 12 months later than scheduled after it. The last flight, the twelfth in the series and the tenth manned flight, ended in November 1966.

Proprietary Project Gemini development costs are exhibited in Campbell and Dreyfus (1967).

3. Apollo

Apollo was NASA's program to land a manned spacecraft on the moon. The earliest formalization of a manned lunar program appeared in NASA's first ten-year plan in late 1959. In that document, NASA authorities envisioned manned *circumlunar* missions

for the late 1960s along with permanent earth-orbiting space stations and the first manned lunar landings in the 1970s.

Table 6. Project Apollo Chronology

Milestone	Date	Notes
Early activities	7/60	NASA announces Project Apollo
	10/60	General Electric and Martin to study feasibility of advanced manned spacecraft
	1/61	NASA completes Project Apollo studies
	5/61	President Kennedy announces lunar landing
Request for proposals	7/61	For spacecraft prime contract
	7/62	For lunar excursion module (LEM)
Source selection	2/61	General Electric for Apollo integration
	11/61	North American for Apollo prime
	3/62	General Dynamics for Little Joe II vehicle
	11/61	Grumman for LEM
Contract start	12/61	Letter contract with North American
	3/63	Definitive contract with Grumman for LEM
Mockup review	4/62	Block I Command Service Module (CSM)
	9/64	Block II CSM
	10/64	M-5 LEM mockup
Preliminary design review	9/63	First LEM mockup review
	4/64	Block I CSM
	1/65	Block II CSM
Design engineering inspection	6/65	CSM
Critical design review	11/65	LEM
	12/65	Block II CSM
Spacecraft flight test	4/64	Suborbital test of "Apollo-shaped" reentry vehicle
	5/64	Suborbital test with CSM boiler plate; orbital test with "Apollo boilerplate model"
	8/65	Suborbital test of CSM-011
End unmanned flight test program	4/66	Apollo 6
Design certification review	3/68	CSM 101, LM-3
Flight readiness review	9/68	Apollo 7
First manned flight	10/68	Apollo 7
Last manned flight end	12/72	Apollo 17

Source: Ertel and Morse (1969); Morse and Bays (1973), Brooks and Ertel (1976); and Ertel, Newkirk, and Brooks (1978).

The very first design issue, which occupied NASA scientists, regarded the route to landing a manned spacecraft on the moon and providing for its return. Three main approaches emerged early in the program, and were researched and argued through June 1962.

Table 7. Apollo Spacecraft Characteristics (Command and Service Module)

Characteristic	Measurement	Source
Shape (Command Module)	3.63 m long, 3.9 m base	a (CSM-101)
(Service Module)	6.88 m long, 3.9 m diameter	a (CSM-101)
Planform area	48.0 m^3	c
Habitable volume	5.94 m^3	c
Dry weight	11,818 kg	b
Empty weight	9,616 kg	c
Structure Weight	32,432 kg	c
Gross weight	41,141 kg	c
Systems weight	6,371 kg	c
Useful load	31,525 kg	c
Maximum design temperature	2316° C	c

[a] Ezell (1988, vol. II).
[b] Campbell and Dreyfus (1967).
[c] Vought Missile Systems Corporation (1972).

Table 8. Apollo Spacecraft Characteristics (Lunar Excursion Module)

Characteristic	Measurement	Source
Shape	3.75 m long, 4.29 m dia. (ascent module) 3.23 m long, 9.45 m wide, (descent module) (opposite legs)	a
Planform area	19.31 m^2	c
Habitable volume	4.53 m^3	c
Dry weight	3,070 kg	b
Empty weight	3,901 kg	c
Structure Weight	1,536 kg	c
Gross weight	13,381 kg	c
Systems weight	2,365 kg	c
Useful load	13,381 kg	c
Maximum design temperature	149° C	c

[a] Ezell (1988, vol. II).
[b] Campbell and Dreyfus (1967).
[c] Vought Missile Systems Corporation (1972).

Direct ascent, traveling directly, nonstop, between the earth and the moon, gained ascendancy early in the program as the preferred approach. Simplicity was its greatest virtue. Its technical challenges involved developing launch vehicles with sufficient power and payload capacity to escape earth's gravity, traverse the distance to the Moon, make a controlled landing there and reverse the process, all without refueling or resupply for its human cargo. Scientists predicted that the most physically demanding part of a direct ascent mission, takeoff from the earth's surface, would require 50 million newtons, more than 11

million pounds of thrust. By comparison, the Atlas launch vehicle, developed for Project Mercury, was capable of 1.6 million newtons (N, .36 million pounds) of thrust.

In 1959, NASA proposed to develop four boosters to meet the agency's future heavy lift needs. The largest, the Nova launch vehicle, was planned with a first stage thrust in excess of the requisite 50 million newton capability.[1]

The second approach, earth orbit rendezvous, was detailed as early as December 1958 by Werner von Braun. In its most general version, a lunar mission would commence fully provisioned from earth orbit, obviating the requirement for a launch vehicle powerful enough to start the trip from the earth's surface and to carry the fuel required to make that leg of the trip. A Saturn launch vehicle would be sufficient for this approach, although the logistics requirements to prepare a vehicle in earth orbit would be nontrivial.

The third approach (lunar orbit rendezvous) entailed descent to the moon in a landing craft, which would later rendezvous with a mother craft for the trip home. This approach was introduced as early as December 1958 by representatives of Vought Missile Corporation. However, it did not gain significant official attention at NASA until December 1960, when personnel from Langley Research Center briefed the Associate Administrator, Robert Seamans on this approach.[2] This approach promised to save weight in as much as the entire spacecraft would not make the round trip to the lunar surface. However, the lunar orbit rendezvous operation was viewed as adding risk to the mission.

The choice of approach to the moon entailed tradeoffs between simplicity (i.e., direct vs. indirect via rendezvous) and launch vehicle cost. The choice of the lunar orbit rendezvous approach was made in July 1962. The critical event leading to its choice might well have occurred a year earlier in May 1961, when President Kennedy announced the goal of a manned lunar landing before the end of the decade. Discussions leading up to July 1962 finally convinced Apollo program managers that lunar orbit rendezvous offered the best chance of meeting the 1969 deadline.

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1 For comparison, the Soviet Union's N-1 launch vehicle was developed for lunar missions, and reportedly generated 45 million newtons. However, it failed to lift off after four attempts made between 1969 and 1972. The Soviet Union's largest launch vehicle to date, the Energia, made its first flight in 1987 and reportedly generates about 31 million newtons in its four strap-on configuration. It reportedly can generate about 60 million newtons in its eight strap-on configuration. Saturn V, U.S.'s most powerful launch vehicle, (reportedly developing over 33 million newtons), first flew in November 1967. The U.S. Space Shuttle is launched using a cluster of two solid rocket motors and three Space Shuttle Main Engines, which reportedly generate about 28.6 million newtons in the aggregate.

2 Various lunar surface rendezvous approaches were also discussed but never came to be the principal contenders.

Table 9. Project Apollo Funding History, 1960-73

Fiscal Year	Category	Funding (millions of constant 1990 dollars)
1960	Advanced technical developmental studies	1
1961	Advanced technical development studies	6
1962	Orbital flight test	358
	Biomedical flight tests	93
	High-speed reentry test	155
	Spacecraft development	292
	TOTAL	905
1963	Command and service modules	1,870
	Lunar excursion module	667
	Guidance and navigation system	176
	Instrumentation and scientific equipment	62
	Operational support	14
	Supporting development	16
	Little Joe II development	48
	Saturn C-I launch vehicles (10)	492
	TOTAL	3,345
1964	Command and service modules	2,831
	Lunar excursion module	700
	Guidance and navigation	475
	Integration, reliability and checkout	315
	Spacecraft support	226
	Saturn I	970
	Saturn IB	762
	Saturn V	3,960
	Engine development	861
	Apollo mission support	680
	TOTAL	11,780
1965	Command and service modules	2,898
	Lunar excursion module	1,217
	Guidance and navigation	406
	Integration, reliability and checkout	124
	Spacecraft support	420
	Saturn I	202
	Saturn IB	1,318
	Saturn V	4,840
	Engine development	834
	Apollo mission support	855
	TOTAL	13,114

Table 9. Project Apollo Funding History, 1960-73 (continued)

Fiscal Year	Category	Funding (millions of constant 1990 dollars)
1966	CSM	2,910
	LEM	1,471
	Guidance and Navigation	544
	Integration, reliability & checkout	163
	Spacecraft support	451
	Saturn I	4
	Saturn IB	1,297
	Saturn V	5,571
	Engine development	635
	Apollo mission support	996
	TOTAL	14,042
1967	Command and service modules	2,528
	Lunar excursion module	2,131
	Guidance and navigation	346
	Integration, reliability and checkout	135
	Spacecraft support	500
	Saturn IB	1,066
	Saturn V	5,123
	Engine development	225
	Apollo mission support	1,100
	TOTAL	13,154
1968	Command and service modules	1,949
	Lunar excursion module	1,710
	Guidance and navigation	484
	Integration, reliability and checkout	285
	Spacecraft support	259
	Saturn IB	627
	Saturn V	4,275
	Engine development	80
	Apollo mission support	1,270
	TOTAL	10,939
1969	Command and service modules	1,401
	Lunar excursion module	1,320
	Guidance and navigation	178
	Integration, reliability and checkout	264
	Spacecraft support	493
	Saturn IB	167
	Saturn V	2,164
	Manned space flight operations	2,212
	TOTAL	8,199
1970	Command and service modules	1,071
	Lunar excursion module	877
	Guidance and navigation	128
	Science payloads	228
	Spacecraft support	647
	Saturn V	1,835
	Manned space flight operations	2,070
	TOTAL	6,856

Table 9. Project Apollo Funding History, 1960-73 (continued)

Fiscal Year	Category	Funding (millions of constant 1990 dollars)
1971	Flight modules	875
	Science payloads	378
	Ground support	165
	Saturn V	674
	Manned space flight operations	1,122
	Advance development	41
	TOTAL	3,255
1972	Flight modules	186
	Science payloads	176
	Ground support	107
	Saturn V	480
	Manned space flight operations	1,036
	Advance development	42
	TOTAL	2,027
1973	Spacecraft	170
	Saturn V	90
	TOTAL	260

Sources: Ertel and Morse (1969); Morse and Bays (1973), Brooks and Ertel (1976); and Ertel, Newkirk, and Brooks (1978).

Although North American Aviation had been selected as the Apollo prime contractor in November 1961 and spacecraft subsystem was already underway in early 1962, major decisions on configuration clearly required the lunar approach decision of July 1962. By November, Grumman Aircraft had successfully competed to be the builder of the Lunar Excursion Module, the vehicle that would make the round trip to the lunar surface from lunar orbit.

Hardware development problems surfaced early in the program. One of the very difficult problems that North American faced concerned its role as systems integrator. Grumman Aircraft faced weight problems in the Lunar Excursion Module. Serious problems were encountered during development of the propulsion units for the prime spacecraft, the Command Service Module, and the Lunar Excursion Module. NASA changed the two contractors' contracts from cost-plus-fixed-fee to cost-plus-incentive-fee types in an effort to improve their performance.

By early 1967, the development problems had reportedly eased to the point where the development schedules were keeping better pace with Apollo mission plans. January 1967 saw an accidental fire aboard a Command Service Module during a simulated countdown kill the crew designated for the first Apollo mission. The accident report, issued in April 1967, called for changes throughout the program, from hardware design to test operations and flight plan.

Table 10. Apollo Applications Funding (Millions of Dollars)

	1966	1967	1968	1969	1970	1971	1972	1973	1974	Total
Space vehicles			126.[illegible]	378.99	524.26					1,030.06
Uprated Saturn I (Saturn I-B) procurement	4.73	98.79								103.52
Saturn V procurement		5.86								5.86
Spacecraft modifications	35.49	65.41								100.90
Experiments										
Definition	163.00	49.50								212.50
Development	27.92	120.11								148.03
Mission support										
Payload integration	0.47	17.59								18.06
Operations	10.88	3.61								14.49
Payloads and experiments			413.28	742.63	645.48					1,155.91
Skylab (workshop cluster)										1,188.46
Orbital workshop						344.42	564.82			909.24
Multiple docking adapter						98.34	111.34			209.68
Airlock module						303.92	276.92			580.84
Apollo telescope mount						49.89	38.87			88.76
Skylab (experiment development)										
Applications and science						126.87	83.26			210.13
Technology and engineering						58.21	80.97			139.18
Biomedical/medical						23.59	13.00			36.59
Skylab (other)										
Payload integration						99.06	116.12			215.18
Program support						53.62	113.39			167.01
Spacecraft						149.79	330.31			480.10
Saturn IB						91.42	141.03			232.45
Saturn V							14.61			14.61
Operations						44.60	34.04			78.64
Skylab Total								1,600.88	525.68	2,126.56
TOTAL	242.49	360.87	540.09	1,121.62		1,967.99	1,918.68	1,600.88	525.68	

Source: Newkirk, Ertel, and Brooks (1977).

The Apollo flight test program commenced in October 1961 with the test flight of a Saturn I launch vehicle. It was not until November 1967 that the Saturn V launch vehicle made its first flight (Apollo 4) carrying an unmanned Command Service Module and Lunar Excursion Module mockup as payload. The first manned test flight (Apollo 7) was earth orbital and launched by a Saturn IB in October 1968. Both earth orbital and lunar orbital flights using Saturn Vs followed, culminating in the lunar landing during Apollo 11 in July 1969. The Apollo lunar exploration program ended in December 1972 with the splashdown of Apollo 17, after 6 successful flights to the Moon and the one mission aborted after liftoff during Apollo 13.

Dreyfus and Campbell (1967) exhibit partial proprietary Project Apollo costs.

4. Skylab

Skylab was a NASA program of the 1960s and early 1970s to operate a manned satellite over extended periods relative to the experience of the earlier manned programs. The program ended in February 1974 with the completion of the third manned mission to the orbital facility. It completed its principal goals in May 1973 with the launch of the Skylab satellite and its occupation by a crew transported to it by an Apollo spacecraft. Before these events, the program underwent considerable evolution and change in the satellite's configuration and design philosophy and in its role in the nation's space program.

Even before the first launch of manned Mercury spacecraft, NASA planners viewed an orbiting space station as integral to the U.S. space program. Its primary mission was to serve as an intermediate staging point for manned missions to the Moon and Mars.

A manned space station persisted in the concepts of NASA planners as a bridge between the Apollo lunar missions and the next large manned exploration project, perhaps a manned mission to Mars. A manned space satellite was also viewed as an opportunity to exploit Apollo hardware developments in continuing space science programs, thus the original designations Apollo Extension System program and Apollo Applications Program for the efforts culminating in the Skylab facility. NASA scientists viewed a sizable orbital facility as essential in accumulating experience with extended space missions. Conducting research in the space environment was initiated in the Mercury program; however, it became a distinct goal when the Gemini program required a formal justification during and following concept definition.

Table 11. Skylab Chronology

Jul 62	Langley Research Center (LAC) hosted a space station forum for NASA researchers.
Mar 63	NASA Headquarters organized a task team to study the concept of a manned, earth-orbiting laboratory.
Apr 63	LRC selected Boeing and Douglas Aircraft to study the Manned Orbital Research Laboatory (MORL)
Dec 64	LRC awarded Boeing a contract to study a manned orbital telescope.
Jun 65	LRC awarded Douglas Aircraft a follow-on study contract for the MORL.
Jul 65	Lockheed delivered a report to the Manned Spacecraft Center (MSC) on a modular multipurpose space station.
Aug 65	Designers at the Marshall Space Flight Center (MSFC) investigated the concept of converting a spent Saturn IVB stage to an orbital workshop.
	President Johnson approved DoD development of the Manned Orbiting Laboratory (MOL).
Sep 65	NASA Headquarters assigned MSC responsibility for spacecraft development, crew activities, mission control, flight operations, and payload integration; MSFC responsibility for launch vehicle, development, and Kennedy Space Center (KSC) responsibility for pre-launch and launch activities.
Apr 66	MSC awarded study contracts to Douglas, Grumman, and Mcdonnell Douglas for orbital workshop (OWS) definition studies.
Aug 66	NASA selected Mcdonnell Douglas to manufacture an airlock module (AM) for the spent-stage OWS design.
Oct 66	AM preliminary design review.
May 67	Preliminary design review for spent-stage OWS.
Nov 67	MSC representatives proposed a dry workshop design as an alternative to the "wet" spent stage design.
Jan 68	Preliminary design review for OWS multiple docking adapter (MDA).
	NASA awarded Perkin-Elmer a contract for the Skylab telescope integration and Martin Marietta a contract for payload integration.
Sep 68	Preliminary design review for Apollo Telescope Mount (ATM).
Feb 69	NASA announced negotiations with North American Rockwell for modifications to 4 Apollo spacecraft for Apollo applications missions.
May 69	Major discussions concerning space station options centered on the "dry versus wet workshop" issue. MFSC director, von Braun and MSC director, Gilruth, opted for dry workshop.
	DoD cancelled the MOL.
Jul 69	The change to the dry workshop design was officially announced.
Aug 69	MSFC definitized the contract with McDonnell Douglas for one OWS and one OWS backup.
May 70	ATM, completed at MSFC
Aug 70	AM, MDA conducted
Sep 70	OWS, conducted
Jan 71	Solar array system, held
Dec 71	MSFC accepted the flight MDA
Sep 72	ATM delivered, OWS arrived by barge to KSC
May 73	Skylab OWS launched
	Skylab 2 manned mission launched for 28-day mission
Jun 73	Skylab 3 manned mission launched for 59-day mission
Nov 73	Skylab 4 manned mission launched for 84-day mission.

Sources: Ezell (1988, vol. III) and Newkirk, Ertel, and Brooks (1977).

The seed for the Skylab facility was the idea of using the upper stage of a spent launch vehicle as the primary structure for a habitable space facility. This idea evolved along several paths, including bundling together several spent stages over time to enhance the capability and survivability of the original facility. A second path, which embodied the final Skylab concept was the orbital cluster, which involved augmenting the spent stage with modules specialized for different purposes.

Table 12. Skylab Spacecraft Characteristics

Spacecraft	Weight (kg)	Length	Diameter[a]	Habitable Volume
Apollo Telescope Mount (ATM)	77,088 kg	4.44 m	3.35 m	
Airlock Module	22,226 kg	5.36 m	6.55 m	
Multiple Docking Adapter	6,260 kg	5.27 m	3.05 m	32.33 m^3
Orbital Workshop	35,380 kg	14.60 m	6.58 m	295.26 m^3
Instrument Unit	2,041 kg	0.914 m	6.6 m	

Source: Ezell (1988, vol. II).

[a] All components but the ATM are cylindrical. The ATM is octagonal with four solar arrays.

A second consideration in the design of the spacecraft involved the "wet" versus "dry" workshop approach. In the wet workshop approach, a spent upper stage would be evacuated of the residual fuel and furnished with hardware that couldn't be built into it and survive the internal prelaunch and launch environments. Some of these furnishings could be carried in an isolated compartment above the functioning upper stage while the remainder would be brought up by the occupants and by resupply missions. In the dry workshop approach the upper stage would function as payload rather than as a launch vehicle. Thus protected from the extremes of the internal launch vehicle environment, it could be fully furnished on the ground and inhabited with less significant post-launch preparation than in the wet workshop approach.

The wet workshop approach dominated planning through most of the concept definition stage of what would become the Skylab program. However, in a remarkable change of direction, NASA administration opted for the dry workshop approach in July 1969. This decision occurred about 3 years after NASA had selected McDonnell Aircraft to build the airlock module for a wet orbital workshop (OWS) and about 28 months after the OWS preliminary design review.

Finally, the Skylab facility was also shaped by the budgetary environment of the time. The Vietnam war was absorbing large portions of the national budget, as was the Apollo program with respect to the NASA budget.

5. Space Shuttle

The Space Transportation System (STS), also referred to as the "Space Shuttle," was NASA's first reusable manned spacecraft.

Post-Apollo planning for the national space program can be traced back to the early days of the Mercury program. However, the post-Apollo program to develop a reusable manned spacecraft is said to have crystallized in official planning in 1969. In September of that year, President Nixon's Task Group delivered its report on options for a national space program. Central to the program were goals to develop a manned earth-orbiting space station and a reusable spacecraft to service it in order to establish a capability for routine access to space. However, the NASA budgets proposed by the Administration were pegged at levels below those required to vigorously pursue these goals, and the President's space policy message delivered in March 1970 indicated interest only in space station and shuttle studies. Congress did not support an expensive new manned space program, which some viewed as an opening buy-in to a more costly Mars-landing program.

Among the reasons reported for the lack of interest in these projects were the lack of public support for large space budgets and for expensive manned space programs. Plans for a manned landing on Mars were compared unfavorably by many vocal opinion leaders with the need for funding social programs and the cost-effectiveness of unmanned missions. The completion of the space race with the manned Apollo landings, leaving the United States with a large lead over the Soviet Union, did not seem to merit the continued expenditures on large projects with debatable benefits and uncertain costs.

George Mueller, NASA's Assistant Administrator since 1963, recognized the need to move from expensive lunar landing extravaganzas to routine, low-cost space operations. Mueller, as well as others, felt that essential to achieving this end was hardware reusability to reduce recurring costs. Up front acquisition costs might be high, but sufficient volume of use would more than compensate in the long run. As a result, Mueller encouraged the Space Task Group to put a space shuttle high on their list of priorities in their recommendations for a national space program.

Early concepts for reusability had included reusable boosters, but by 1971 attention had narrowed to flyback, manned orbiters boosted into space by a flyback, manned launch vehicle. NASA planners, between 1970 and 1972, rejected the concept of a fully reusable system as too expensive for a budget-minded Congress and Administration.

Table 13. Space Shuttle Chronology

Milestone	Date	Source	Notes
Preliminary studies	1/69	a	Nine month Phase A study contracts to General Dynamics, Lockheed, North American, McDonnell Douglas
	2/70	a	Phase B definition studies to North American, McDonnell Douglas
Program start	3/70	a	Shuttle program office established
	1/71	a	President Nixon endorses Shuttle program
Request for proposals	3/71	a	SSME development to Aerojet, Rocketdyne, Pratt & Whitney
	3/72	a	Orbiter development
	4/73	a	External tank
Source selection	7/71	a	Rocketdyne for SSME
	7/72	a	North American as prime contractor
	8/73	a	Martin Marietta for external tank
Contract start	8/72	a, b	NASA authority to proceed
	4/73		Letter contract with North American; definitive contract on 4/73
Program requirements review	11/72	a, b	
System requirements review	8/73	a, b	Orbiter
Preliminary design review	11/74	b	Approach and landing test
	2/75	a, b	Orbital flight
First orbital rollout	9/76	a	Orbiter 101 (Enterprise)
First SSME delivery	6/77	a	To NSTL
Flight test start	2/77	a	Taxi tests, inert captive
First free flight	8/77	a	Unmanned
Complete flight test program	1/78	a	
Complete main propulsion testing	12/78	b	
STS-1 flight readiness review	10/80	a, b	

[a] Ezell (1988, vol. III) and NASA Press Kit (1988).
[b] NASA, Office of Public Relations (1977).

Two studies by Mathematica, Inc., an economics consulting firm, were significant in this change. The first study, delivered in May 1971, concluded that the fully reusable shuttle would be only marginally cost-effective, a margin that could be wiped out in the event of even a minimal cost overrun. Following this study, NASA administrators responded to resistance within the Congress and within the Administration by directing industry study contractors to design lower cost options. Reductions in the size of the orbiter necessitated storing its propellants in a large external tank, which would be discarded when empty. The favorable Mathematica study of this alternative, although predicated on questionable assumptions (e.g., 714 flights during a 12-year planning period) was reported to the NASA Administrator, who used it to make the case for the

shuttle program. President Nixon approved the program in January 1972 because the new program was economically sustainable.

Accompanying this victory were funding constraints that would prove difficult in the future. As Grey (1979) characterizes:

> The final compromise decision, arrived at in relative haste for so large an effort, constrained NASA to proceed with a decade-long multi-billion dollar program on the basis of some rather sketchy technical data. Again, they had "bought in" to a complex-technology program and were stuck with it. And they *were* stuck. Congress, in the FY 1973 budget approval process, nailed down the lid on what NASA had agreed to; a first orbital flight in 1979, at a total development cost of $5.22 billion (1972 dollars), and a total program cost (including the development costs, five orbiters, the necessary boosters and tanks, and launch facilities) of $7.5 billion (1972 dollars). The Congressional debate also put an absolute limit of 20 percent on cost overruns (one billion dollars), which NASA was forced to accept, despite the high level of technological risk implied by the shuttle's performance. The compromise also did not allow sufficient funds for development of the reusable tug needed for high orbit transfers; a point that did not receive much attention at the time, but later came back to plague NASA's shuttle marketing effort. [pp. 79-80]
>
> Despite the excellent technical accomplishments of Tischler's Shuttle Technologies Office, the politics of 1971 forced NASA's retrenchment from a fully reusable two-stage shuttle, to the stage-and-a-half, partly reusable TAOS compromise. Much technological backing and filling was necessary, there just wasn't enough time. The resulting ironbound commitment implied by Nixon's January 1972 announcement and the subsequent Congressional budget debate locked NASA into the manacles of a bare-bones development budget. The nation's most important space project, on the basis of only a few month's technical integration of truly advanced technologies, was going to have to be done on a literal shoestring. There was practically no margin for error for the next nine years. [p. 85.]
>
> As late as August 1971 the bulk of NASA's design efforts were still concentrated on the all-reusable two-stage flyback configuration, as Del Tischler put it, "because of the lack of sufficient funds to do much else." Tischler insisted that much of his technology could be applied to a broad range of flyable reentry concepts. In the few months before the switch was made there just wasn't enough time to tie down all the details of the new system. Many of the cost estimates on which NASA had agreed to mortgage its future on were based on the sketchiest of preliminary design data.
>
> At the time of Nixon's decision, the shuttle compromise configuration had evolved into a flyable orbiter having a triangular (delta) wing and using liquid propellant (hydrogen-oxygen) rockets for takeoff. The orbiter was to be boosted in a vertical launch by one of two possible schemes, depending on costs and technology still to be evaluated.
>
> The hurriedness of the budgetary decision-making process that led to this compromise became evident almost immediately. By March 1972 the booster decision was made, but neither of the original options, that had formed the basis for the already locked-in budget, were selected. Instead, NASA decided on another compromise dictated almost wholly by cost and reliability considerations; recoverable solid-rocket propellant booster rockets. [pp. 89-90.]

Table 14. Space Shuttle Orbiter Characteristics

Characteristic	Measurement	Source
Inert mass	68,492 kg	a
Gross mass	93,894 kg	a
SSME average thrust	1.67 mn (SL)	a
SSME ISP	263.2 sec (SL)	a
SSME chamber pressure	2,970 psia (205 bar)	a

[a] Isakowitz (1991).

Table 15. Space Shuttle Main Engine Programmed Funding for Design and Development, 1970-1978

Year	Funding (millions of 1990 constant-year dollars)
1970	15.91
1971	—[a]
1972	152.03[b]
1973	129.29
1974	244.86
1975	255.88
1976	346.79
1977	405.21
1978	407.24

Source: Ezell (1988, vol. III).

[a] Authorization figures not broken down to include this category. About $74,470,000 programmed for engine definition.

[b] May not include $46,520,000 for engine and vehicle definition.

NASA issued a request for proposals in March 1972 for the Shuttle system as a whole and selected North American Rockwell from the four applicants in July 1972. The development contracts for the Shuttle's main engines had been awarded earlier to North American's Rocketdyne division in July 1971. The contract for the expendable tank, which supplies fuel for the Shuttle's main engines, went to Martin Marietta in August 1973. Finally, the development contract for the Shuttle's solid rocket booster was awarded to the Thiokol Chemical Company in November 1973.

The first flight schedule, released in April 1972, predicted six flights in 1978, following delivery of the first orbiter, a test article, in mid-1976 for horizontal flight testing. Sixty flights per year between 1983 and 1987 would bring the total number of flights during the first ten years of operation to over 400.

The Shuttle orbiter development program faced three principal technology challenges: the onboard flight control system, the high-performance rocket engine, and the thermal protection system.

Unlike earlier manned programs, Mission Center ground control of the Shuttle missions was not practicable, given the complexity and variety anticipated for the missions. The solution sought was to move computer-based flight control onboard the orbiter. Such an approach necessitated fault-tolerant processing for critical flight control functions. Advances in microprocessor and other computer-related technologies provided the background for the engineering solutions to this problem.

The orbiter main engine requirements made several demands on its rocket engines, which made their development a technological challenge (Grey, 1979). First, the engine assembly had to fit within the Shuttle orbiter body, whose size and shape were fixed by aerodynamics requirements. Thus, the very high engine chamber pressures necessary for the high thrust levels had to be designed into a small, minimal weight package. Similarly, the exhaust nozzles had to fit within the orbiter design envelope. A wholly new engine cycle was an inevitable requirement.

A second difficult demand to be made on the rocket engine design was reusability. The service life planned for the orbiter, over 50 missions, translated into an engine service life of over six hours. This compared to the few minutes required for expendable rocket engines of comparable performance.

Finally, the reusability of the orbiter demanded new thinking about protecting the orbiter from the thermal challenge of reentry. The solution through the Apollo program had been the use of ablative materials; however, the need to contain operating costs precluded this approach for the Shuttle. Grey (1979) characterizes the development, testing, and integration of the refractory "carbon-carbon" tiles into a high-performance aircraft as "a management engineering accomplishment of the highest order."

Much of the work to address these issues had already started by the time President Nixon gave his go-ahead in January 1973. The development of the orbiter's main engines, which proved to be the pacing development for meeting the first-flight schedule, turned out to pose a difficult challenge. Rocketdyne, the contractor chosen for the engine development, had little experience with the staged-combustion cycle approach they selected to pursue.

As early as 1975, the Shuttle main engine's development problems were becoming apparent. By September of that year, only 19 of the 374 engine tests required for final flight certification had been completed. NASA reported that padding in the schedule was sufficient to accommodate the delay, and the FY 1978 budget incorporated reprogramming of funds to meet the unexpectedly higher costs. A National Research Council report on the Shuttle main engine recognized the ambitious character of the development schedule, while pointing out the good prospects of what was a new technological development. A period of successful engine tests in mid-1978 was followed by a series of failures in the end of that year. As a result, the earliest possible launch was postponed to November 1979.

The first orbiter was rolled out in September 1976 and commenced the test program with the first of five unmanned captive tests in February 1977. However, Rockwell did not complete the assembly of the second orbiter until March 1978, and the longer-than-expected qualification of the vehicle delayed the first flight of the orbiter until April 1981. As recently as 1974, the first flight date had been publicly pegged to be as early as March 1979, although a more realistic internal estimate held at the same time pegged the date to June 1979 (Grey 1979).

III. LAUNCH VEHICLES

A. COST MODELS

We examined three launch vehicle cost models during this study: the launch vehicle portion of the NASA Cost Model (Planning Research Corporation 1990a), a rocket propulsion cost model developed at Tecolote Research (Sjovold and Morrison 1989), and the initial version of the Launch Vehicle Cost Model (LVCM) also developed at Tecolote Research (Takayesu et al. 1989). The NASA Cost Model (NASCOM) is a weight-based model, while the Tecolote models include performance and weight variables.

NASCOM has CERs for liquid rocket engines and for complete launch vehicles. For both categories costs are separated into non-recurring or DDT&E cost and recurring or flight unit cost. In all the equations, weight is measured in pounds. The CERs are presented below. NASCOM recommends these relationships only for attaining "ball park" precision. Since these are not fitted equations, there are no statistics presented with them.

Liquid Rocket Engines:

$$\text{DDT\&E Cost} = 18363.4(\text{WT})^{0.5}$$

$$\text{Flight Unit Cost} = 57.6(\text{WT})^{0.7}$$

Launch Vehicles:

$$\text{DDT\&E Cost} = 3840.1(\text{WT})^{0.5}$$

$$\text{Flight Unit Cost} = 19.2(\text{WT})^{0.7}$$

In the CERs where Cost = C_1*(Weight)^{C_2}, C_1 is the "average first unit cost" in thousands of 1989 dollars and C_2 is an assumed slope based on engineering judgement and cost experience. The liquid rocket engine equations are based on nine data points while the launch vehicle equations are based on four. The data used in the equations are proprietary. Analysts should consult Volume II of NASCOM for more information on the data.

The Tecolote work examined here was motivated by the failings of most launch vehicle cost models which are based on a small number of data points and are either weight

based or utilize subjective inputs that require experienced analysts. They were looking for a more objective cost model.

For the propulsion cost model, Tecolote segregated the data into pump-fed liquid engines and solid rocket motors. Pressure-fed engines are not covered by the model. The systems used are listed in Table 16. The pump-fed liquid engines used in the model are listed in Table 17 and the solid rocket motors are in Table 18. The cost data are proprietary.

Table 16. NASCOM Equation Data Points

Launch Vehicles	Liquid Rocket Engines
Centaur-D	F-1
Centrur-E	J-2
Enternal Tank	RL-10
Inertial Upper Stage	Space Shuttle Main Engines
S-IC	
S-II	
S-IVB	
Solid Rocket Booster	
Solid Rocket Motor	

Table 17. Liquid Engine Data Points, Tecolote Model

Engines	Production	Development
Agena	X	X
Atlas Booster	X	
Atlas Sustainer	X	
Atlas Sustainer + Booster		X
RL-10 A-3-3 (Centaur)	X	X
Thor	X	
Titan III, Stage 1	X	
Titan III, Stage 2	X	
RS-27 (Thor-Delta Booster)	X	
H-1 (Saturn 1)	X	
F-1 (Saturn 5)	X	X
J-2 (Saturn 1 and 5 Upper Stage)	X	X
SSME (Shuttle Maine Engine)	X	X
Titan I S-1, S-2		X
Titan II S-1, S-2		X

For liquid engines, Tecolote provided a CER for development cost and another for production cost. For solid rocket motors, there are two CERs for both development and production cost.

Table 18. Solid Rocket Motor Data Points, Tecolote Model

Engines	Production	Development
Minuteman I, II, III Stage 1	X	X
Minuteman I Stage 2	X	X
Minuteman II, III Stage 2	X	X
Minuteman I, II Stage 3	X	X
Minuteman III Stage 3	X	X
Polaris A2 Stage 1	X	
Polaris A2 Stage 2	X	
Polaris A3 Stage 1	X	
Polaris A3 Stage 3	X	
Poseidon C3 Stage 1	X	
Poseidon C3 Stage 2	X	
Titan 3C, D Stage 0	X	
Titan 34D Stage 0	X	
System A	X	X
System B	X	X
System C	X	X
Trident 1 S-1	X	
Trident 1 S-2	X	
Trident 1 S-3	X	

1. Pump-Fed, Liquid Engines

Development cost in millions of 1987 dollars, including G&A and fee.

$$C_{dev} = 52.95\,[CAC(150)]^{.939}\,N_p^{.618}$$

$N = 7$ Adj $R^2 = .9419$ SEE = .337 (in log space)

where

C_{dev} = FSED cost for the engine system

$CAC(150)$ = cumulative average unit cost of 150 units calculated from the production CER

N_p = number of full-up engines to be built for the FSED program.

Produc..on cost, in millions of 1987 dollars, including G&A and fee.

$$CAC(Q) = .00124\,Q^{-.251}\,R^{-.132}\,W^{.618}\,(PPSI*NT)^{.347}$$

$N = 11$ Adj $R^2 = .9895$ SEE = .1276 (in log space)

where

$CAC(Q)$ = cumulative average unit cost of Q units

R = nominal annual production rate, units/yr

W = dry weight of the engine system, lbs.

(PPSI*NT) = a composite variable of the product of pump discharge pressure in PSI and the number of coolant channels or number of tubes (NT) in the chamber and throat sections.

2. Solid Rocket Motors

Development cost, in millions of 1987 dollars without fee.

$$C_{dev} = 17.36\,[CAC(150)_{WT}]^{1.03}\,N_p^{.756}$$

N = 8 Adj R^2 = .9063 SEE = .197 (in log space)

or

$$C_{dev} = 5.389\,[CAC(150)_{WN}]^{1.103}\,N_p^{.990}$$

N = 8 Adj R^2 = .9269 SEE = .1737 (in log space)

where

C_{dev} = FSED cost for the motor

$CAC(150)_{WT}$ = cumulative average unit cost of 150 units calculated by the production CER based on total motor weight

N_p = number of full-up motors to be built for the FSED program

$CAC(150)_{WN}$ = cumulative average unit cost of 150 units calculated by the production CER based on nozzle weight.

Production cost, in millions of 1987 dollars without fee.

$$CAC(Q) = .397\,Q^{-.215}\,W_t^{.509}\,N_n^{.557}\,e^{.705D_1}\,e^{.367D_2}$$

N = 18 Adj R^2 = .9497 SEE = .214 (in log space)

or

$$CAC(Q) = .267\,Q^{-.215}\,W_n^{.388}\,N_n^{.281}\,e^{.951D_1}$$

N = 16 Adj R^2 = .9803 SEE = .137 (in log space)

where

CAC(Q) = cumulative average unit cost of Q units

W_t = total weight on motor including propellant, K lbs

N_n = number of nozzles

D_1, D_2 = dummy variables for motor case material where

D_1 = D_2 = 0 for steel

$D_1 = 1, D_2 = 0$ for kevlar

$D_1 = 0, D_2 = 1$ for glass or other

W_n = weight of nozzles and thrust vector control hardware, lbs.

Subsystem CERs would provide the insights and level of detail necessary for improved cost estimating. Pressure-fed liquid engine CERs should also be examined.

We also examined the documentation for the initial version of the Tecolote Launch Vehicle Cost Model (LVCM). The model is PC based and uses an off-the-shelf data software package called Mainstay. The model is not yet fully operational. The goal is to allow the user to establish a total system cost by building estimates at the subsystem level. The CER library which the model draws on currently holds thirty-four CERs primarily for propulsion and structures. The equations from Tecolote paper TR-012 just discussed are included in the model. CERs for avionics are absent, and other modules necessary for forming a complete cost build-up are as yet incomplete. Still, the motivation for the model is the same as for the TR-012 study: the need for a model that is not strictly weight based and one that does not utilize subjective inputs that require experienced analysts.

In addition to the data bases from NASCOM and the Tecolote studies, Planning Research Corporation (PRC) has produced the Launch Vehicle Catalog/Data Base for Goddard Space Flight Center (Planning Research Corporation 1991). A continuing effort at PRC, the data base covers technical, programmatic and some cost data. In Table 19 is a list of the vehicle categories used and the number of data points in each category for which cost data are available. For example, the data base contains recurring costs for five versions of the Delta launch vehicle. All costs provided are recurring costs. The data are limited distribution and are not presented here.

Table 19. Categories of PRC Launch Vehicle Cost Data Base

Launch Vehicle Category	Number of Versions
Space Shuttle (STS)	1
U.S. Expendable Launch Vehicles	
Atlas	2
Delta	5
Scout	1
Titan	10
Small ELV Commercial	11
Upper Stages	5
Sounding Rockets	18
Foreign Launch Vehicles	2
Historical U.S. Launch Vehicles	40

B. PROGRAMS

1. Atlas

Atlas development began in 1946 as an intercontinental ballistic missile (ICBM). The government cancelled the program a year later, but reinstated it in 1951. The Atlas A, B, and C versions were strictly development and test vehicles, while the Atlas D, E, and F models functioned as operational ICBMs during the 1960s.

Early in its development, the Atlas was selected for a role as launch vehicle in the U.S. space program. A modified Atlas B flew in the U.S. Air Force's Project Score communications satellite program in 1958, and a year later, the Atlas took its place as the heavy lift vehicle in the newly-initiated Project Mercury space program.

Table 20. Atlas Launch Vehicles

Model	Description
A	ICBM single stage R&D vehicle
B, C	ICBM 1 1/2 stage R&D vehicle
D, E, F	ICBM
LV-3A	D with Agena upper stage
LV-3B	Man-rated D for Project Mercury
SLV-3	Rehability-improved LV-3A
SLV-3A	SLV-3 stretched by 117 inches
LV-3C	D with Centaur D upper stage
SLV-3C	LV-3C stretched by 51 inches
SLV-3D	SLV-3C with Centaur D-1A, and with integrated Atlas/Centaur avionics
G	SLV-3D with 51-inch Atlas-stretch
H	SLV-3D with E/F avionics, without Centaur upper stage
I	G strengthened for 14 ft. payload fairing and with ring laser gyroscope
II	I with 108-inch Atlas-stretch, uprated engines, 36-inch Centaur-stretch, and other changes
II A	II with uprated Centaur RL-10 engines and nozzels
II AS	II A with four Castor IV A strap-ons

Source: Isakowitz (1991).

Following their replacement in the late 1960s by the Minuteman ICBM, the Atlas D, E, and F models entered the launch vehicle inventory. They joined a family of Atlas models whose developmental line had departed from the ICBMs at the Atlas D model. The Atlas LV-3A, the first vehicle in this developmental branch, carried the U.S. Air Force's Project Score payload. A man-rated variant, designated the LV-3B, carried nine Mercury payloads, including four manned flights.

The LV-3A carried a variety of payloads during the early 1960s using the Agena upper stage. These payloads included the ERS satellites and Ranger and Mariner probes. Meanwhile, another direct successor of the LV-3A, the SLV-3, entered service with Project Gemini and carried Lunar Orbiter probes to the Moon.

Table 21. Atlas Launch Vehicle Characteristics

	Atlas I	Atlas II
System height	Up to 43.9m	Up to 47.5m
Booster/Centaur height	22.2m/9.15m	3.05m/3.05m
Booster/Centaur width	3.05m/3.05m	3.05m/3.05m
Payload fairing	3.3m × 10.4m, or 4.2m × 12.0m	3.3m × 10.4m, or 4.2m × 12.0m
Number of booster engines	3 thrust chamber 2 turbine-driven pumps 2 verniers	3 thrust chamber 2 turbine-driven pumps
System gross mass	164,300 kg	187,600 kg
Booster/Centaur gross mass	145,700 kg/15,600 kg	165,700 kg/18,800 kg
Booster/Centaur propellant mass	138,300 kg/13,900 kg	155,900 kg/16,700 kg
<u>Performance</u>		
Geotransfer orbit (28°)	2680 kg	2810 kg
Geosynchronous orbit	570 kg	610 kg
With Apogee Kick Motor	1,400 kg	1500 kg
Circular sun-synchronous orbit (705 km)	n/a	4030 kg
<u>Average Thrust</u>		
Booster (SL)	1.68×10^6N	1.84×10^6N
Sustainer (SL)	2.69×10^5N	2.69×10^5N
Centaur	1.47×10^5N	1.47×10^5N
<u>ISP</u>		
Booster (SL)	259.1 sec	261.1 sec
Sustainer (SL)	220.4 sec	220.4 sec
Centaur (vac)	444.4 sec	442.4 sec
<u>Chamber pressure</u>		
Booster	639 psia (44.1 bar)	639 psia (44.1 bar)
Sustainer	735 psia (50.7 bar)	735 psia (50.7 bar)
Centaur	465 psia (32.1 bar)	465 psia (32.1 bar)
<u>Nozzle expansion rato</u>		
Booster	8:1	8:1
Sustainer	25:1	25:1
Centaur	61:1	61:1

Sources: Isakowitz (1991) and General Dynamics (1991).

Finally, a second line of Atlas D modifications started with the LV-3C, which incorporated the Centaur upper stage. The Atlas LV-3C, which carried Lunar Orbiter and Surveyor probes, led to the SLV-3C and -3D models, which carried payloads between 1967 and 1980, and then to the current line of Atlas I, II, II A, and II AS models.

Estimated launch prices for four Atlas versions are listed in Table 22.

Table 22. Estimated Atlas Launch Prices

Version	Price (Millions of 1990 Dollars)
Atlas I	\$65–\$75
Atlas II	\$70–\$80
Atlas IIA	\$80–\$90
Atlas IIAS	\$110–\$120

Source: Isakowitz (1991).

2. Thor

Douglas Aircraft Company developed the Thor intermediate range ballistic missile (IRBM) starting with a contract award in December 1955 and ending with the delivery of the first missile in October 1956, the first test launch in January 1957, and the attainment of its required 3200 km range in October 1957.

However, as early as November 1957, Thor entered the U.S. space program by pairing it with one of several upper stages. A Thor-Able I combination carried a Pioneer 1 satellite in October 1958 and a Pioneer 2 satellite in November 1958. The Able upper stage was a derivative of the U.S. Air Force's Vanguard vehicle.

Thor vehicles paired with Agena-B upper stages carried the Alouette 1 satellite in September 1962 and the Nimbus 1 satellite in August 1964. The restartable Agena-D replaced the Agena-B in October 1965 with the launch of OGO 2. Overall, the U.S. Air Force was the principal user of the Thor-Agena vehicle. The other upper stages used by the Air Force included the Burner II, Burner IIA, and Altair, while the Navy used the Ablestar upper stage.

The pairing of Thor with Delta upper stages proved to be the most longstanding relationship. Starting in May 1960 with the launch of an Echo satellite and proceeding through a number of modifications, the Thor-Delta pairing evolved into the current Delta Launch Vehicle.

Table 23. Thor Launch Vehicle Variants

Model	Description
Thor	
Thrust-Augmented Thor (TAT, DSV-2C)	Thor plus three Castor solid rocket booster plus improved main engine
Long-Tank TAT (LTTAT, DSV-2L)	TAT with tanks stretched by 11 ft.
Long-Tank Thrust-Augmented Thor (Thorad)-Agena D	Thor vehicle stretched by 4.6 ft.

Sources: Ezell (1988, vol. II) and Isakowitz (1991).

Table 24. Thor Launch Vehicle Characteristics

	Thor (with Able)	TAT	Thorad
Height	17 m	17 m	21.6 m
Diameter	2.4 m	3.4 m (with Castors)	
Launch weight	48,978 kg	48,777 plus 12,653 kg	70,000 plus 12,653 kg
Thrust	676,096 N (MB-1 engine)	765,056 N (MB-3 engine)	765,056 N (MB-3 engine)

Source: Ezell (1988, vol. II).

3. Saturn

Saturn launch vehicle development arose out of Wernher von Braun's program at the U.S. Army's Ballistic Missile Agency to build a large, clustered-engine booster. The goal of the program was to acquire a capability to put payloads weighing up to 18,000 kg into earth orbit, or payloads weighing up to 5400 kg into an escape trajectory. Such a booster would develop over 6.5 million N of thrust in its first stage. This was four times the 1.6 million N of thrust developed by the Atlas SLV-3 used in Project Mercury.

The inital Saturn studies commenced in April 1957 and led up to a development proposal by the U.S. Army to the Department of Defense in December 1957. The Advanced Research Projects Agency authorized the development of a 6,672 million N class booster, then known as Juno V, in August 1958. The Army Ballistic Missile Agency managed the program until November 1959 when NASA assumed its technical direction.

The Saturn I first stage consisted of a cluster of eight Rocketdyne H-1 engines, which evolved from the Thor-Jupiter engine as a result of a development contract awarded in September 1958. The first full-power test firing of an H-1 engine was made in December 1958 and Rocketdyne delivered the first production H-1 to the Army in April 1959.

NASA expanded the Saturn program in December 1959 from the single model then in development to a family of launch vehicles. A month later this Saturn program was approved and was given the highest national priority.

Thus, Rocketdyne received a contract in January 1959 to develop a larger single-chamber engine, designated the F-1. Five F-1 engines would later power the Saturn V first stage with a combined thrust of 33,360,000 N. Rocketdyne delivered the first production F-1 engine to NASA in October 1963.

The original Saturn I launch vehicle, then designated the C-1 model, consisted of two stages. The first, designated S-1, embodied von Braun's 6.7 million N booster concept. NASA's Marshall Space Flight Center designed this stage, and manufactured the first eight articles before transferring this responsibility to the Chrysler Corporation. Douglas Aircraft received the contract to develop the second stage, designated S-IV, in July 1960.

Four test launches commencing in October 1961 focused on the large S-1 stage. However, the next six flights, starting in January 1964, tested the complete launch vehicle, and culminated in five flights between May 1964 and July 1965 that carried Apollo boilerplate hardware and Pegasus satellites.

The Saturn IB launch vehicle represented an intermediate step between the pioneering Saturn I and the launch vehicle that would be required for the operational Apollo program. Saturn IB, originally designated Saturn C-IB, was an uprated Saturn I. The first stage, designated S-IB, consisted of eight Rocketdyne H-1 engines, whose aggregate thrust was nearly 500,000 N greater than those powering the S-1. In addition, the six Pratt & Whitney RL-10A3 engines, with aggregate thrust of 400,000 N were replaced by a single Rocketdyne J-2 engine. Originally capable of 890,000 N of thrust, Rocketdyne uprated the J-2 engine to one million N.

The first test launch of a Saturn IB took place in December 1965 and carried an Apollo spacecraft in order to test the command module heat shield. After three additional test flights of the Saturn IB, the AS-205 vehicle carried a crew of three in the first manned Apollo test flight, Apollo 7, into an earth orbital mission lasting eleven days.

Table 25. Saturn Launch Vehicle Characteristics

	Saturn I	Saturn II
System height (excluding spacecraft, tower, and instrument unit)	36.6 m	85.0 m
Stage 1 height	25.0 m	42.1 m
Stage 2 height	12.2 m	24.8 m
Stage 3		
System gross mass	$5.06 \times .10^6$ kg	$2.91 \times .10^6$ kg
Stage 1 gross mass	$4.44 \times .10^5$ kg (S-IB)	$2.21 \times .10^6$ kg
Stage 2 gross mass	$4.35 \times .10^4$ kg	$4.86 \times .10^5$ kg
Stage 3 gross mass		$1.19 \times .10^5$ kg
Stage 1 propellant mass	$4.08 \times .10^5$ kg (S-IB)	$2.08 \times .10^6$ kg
Stage 2 propellant mass	$1.06 \times .10^5$ kg (S-IVB)	$4.50 \times .10^5$ kg
Stage 3 propellant mass		$1.08 \times .10^5$ kg
Performance		
Earth orbit	9070 kg (555 Km) 16,598 kg (Saturn I-B, 195 km)	129,248 (195 Km)
Engines		
Stage 1	eight H-1	five F-1
Stage 2	one J-2	five J-2
Stage 3		one J-2
Average thrust		
Stage 1 (each engine, SL)	$8.34 \times .10^5$ N	$6.9 \times .10^6$ N
Stage 2 (each engine, vac)	$6.67 \times .10^5$ N	$1.023 \times .10^6$ N
Stage 3 (vac)		
ISP		
Stage 1 (SL)	232 sec (S-IB)	264 sec
Stage 2 (vac)	444 sec (SL)	425 sec (vac)
Stage 3		
Chamber pressure		
Stage 1 (SL)	689 psia (47.5 bar, S-IB)	950 psia (65.5 bar)
Stage 2 (vac)	703 psia (48.5 bar)	632 psia (43.6 bar)
Stage 3 (vac)		632 psia (43.6 bar)
Nozzle expansion ratio		
Stage 1	8:1	16:1
Stage 2		28:1
Stage 3		28:1

Sources: Isakowitz (1991) and Ezell (1988, vol. II).

Table 26. Saturn R&D Funding History (Millions of 1990 Constant-Year Dollars)

	Army	NASA																	NASA
Fiscal Years	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	Run-Out Total
Funding (Code)																			
Saturn I (931)[a]	129.4	387.2	586.4	1,073.8	1,379.4	921.7	166.0	0.9											4,515.4
Saturn IB (932)					99.2	726.2	1,341.9	1,176.8	875.1	424.2	170.5								4,813.9
Saturn V (933)				314.2	1,835.8	3,906.8	4,964.0	5,229.8	4,603.9	3,586.4	2,139.5	1,809.9	834.5	661.1	58.7				29,944.6
Engine Devel (940)	62.8	143.3	467.8	582.9	732.2	861.0	862.6	630.3	224.6	86.1	28.7	25.4							4,644.9
Launch Ops (950) & Sys Engr (980)				11.8	10.8														22.6
Spacecraft (Lunar Rover) (914)										0.8	1.2	73.1	67.3	2.4					144.8
Total	192.2	530.5	1054.2	1,982.7	4,057.4	6,415.7	7,334.5	7,037.8	5,703.6	4,097.5	2,339.9	1,908.4	901.8	663.5	58.7				44,086.2
Costs																			
Saturn I	46.5	195.1	360.1	571.1	1,336.0	1,661.4	338.7	24.1	1.4	-1.3	-0.4	-0.8	-0.4	-0.3					4,484.7
Saturn IB					14.6	384.4	1,261.5	1,442.3	982.2	456.5	195.2	4	3.2	1.0	1.6	-0.3	-1.3		4,744.9
Saturn V				123.4	1,243.9	3,309.3	5,184.9	5,559.2	4,731.6	3,328.5	2,644.8	1,651.6	926.4	669.1	298.2	-17.6	-0.3	-2.5	29,650.5
Engine Develop	22.6	133.7	362.5	608.1	723.6	830.4	833.0	697.5	262.1	97.9	53.9	34.8	0.4	0.3	0.3				4638.5
Launch Ops/Sys Engr					2.7	14.5	4.1												21.3
Spacecraft (Lunar Rover)												63.6	75.5	4.0					143.1
Total	69.1	328.8	722.6	1302.6	3,320.8	6,200.0	7,622.2	7,723.1	5,977.3	3,881.6	2,893.5	1,753.2	1005.1	674.1	300.1	-17.9	-1.6	-2.5	43,683.0

Source: Bilstein (1980).

Note: Later-year credits result from final contract audits. Audit agency workload delayed contract close-out several years in some cases.

[a] Includes Army (pre-NASA) funding of $84.9 million (TY).

The last Saturn model, the Saturn V, originally called the C-5 model, was a three stage vehicle. The first stage, S-IC, carried the five Rocketdyne F-1 engines with over 33 million N aggregate thrust. The second stage, designated S-II, carried five Rocketdyne J-2 engines with an aggregate thrust of five million N. The third stage, designated S-IVB, had been the second stage of the Saturn IB. The three stages were respectively produced by Boeing, North American, and Douglas.

The first test launch of a Saturn V launch vehicle took place in November 1967, and carried the unmanned Apollo 4 spacecraft. The Apollo 6 spacecraft test launch saw a premature second stage engine shutdown and a third stage restart failure. The third Saturn V launch carried the crew of Apollo 8 to the first manned lunar orbit in December 1968.

4. Delta

The Delta launch vehicle evolved from the pairing of the Thor immediate range ballistic missile with the Delta upper stage for the purpose of carrying satellites into earth orbit. The first such mission took place in May 1960 when a Thor-Delta launch vehicle carried an Echo satellite into space. The point at which the Thor-Delta pairing should be uniquely identified as a Delta launch vehicle is partly a matter of definition.

The numerical Delta nomenclature for the entire launch vehicle (see Table 27) has been applied to launch vehicles referred to as "Long Tank Thrust-Augmented Thor-Delta," e.g., the 1604, 1900, 1913, and 1914 vehicle classes, as well as the "1000-series" vehicles.

However, beginning with the "2000-series" launch vehicles, and the 2914 launch vehicle class in particular, the launch vehicle as a whole is referred to as a Delta-type upper stages. Examination of the Table 27 suggests the lack of Delta evolution and variation. The early development included increasing the number of solid-rocket booster strap-ons from three to six and eventually to nine, which has become the standard.

The principal families of Delta launch vehicles are distinguished by the first digit of their designation, starting with the Castor II, long tank configuration, i.e., the "0" series, and progressing through 6920 and 7920 series, which McDonnell Douglas has developed for the U.S. Air Force under the name "Delta II." NASA has used vehicles from the 3920 class, although augmented with the PAM-D third stage.

The first evolution of the Delta launch vehicle took place in the 2000-series models, in which the Aerojet AJ10-118F second stage engine was replaced with the TRW TR-201

engine, which was a derivative of the Apollo descent module rocket. In addition, the Rocketdyne RS-27 engine replaced the less-powerful MB-3 engine.

The next major Delta model evolution was the addition of the McDonnell Douglas PAM-D third stage, which was originally developed to transfer Space Shuttle satellites from low-earth orbit. With the replacement of TR-201 second stage engine with the Aerojet AJ10-118K. The PAM-D gave the Delta the capability of executing missions with the larger Shuttle-class payloads.

The U.S. Air Force 6920- and 7920-series launch vehicles are growth versions of the 3920/PAM-D Delta. Their development was prompted by the continuing requirement to place global positioning satellites into orbit after the Challenger accident and the series of launch vehicle failures that followed it. The 7925 model Delta II features graphite-epoxy motors (GEM) for the solids and a main engine with a greater thrust rating than the 6925 model because of an increased-expansion-ratio nozzle.

The estimated launch price for a 6925 or a 7925 is $45 million to $50 million in 1990 dollars (Isakowitz 1991).

Table 27. Delta Launch Vehicle Model Nomenclature

Delta	1st Digit - First Stage Type Augmentation
	2nd Digit - Number of Augmentation Motors
	3rd Digit - Type of Second Stage
	4th Digit - Type of Third Stage
First Digit	0 - Castor II. Long Tank, MB-3 Engine
	1 - Castor II. Extended Long Tank, MB-3 Engine
	2 - Castor II. Extended Long Tank, RS-27 Engine
	3 - Caster IV. Extended Long Tank, RS-27 Engine
	4 - Castor IVA. Extended Long Tank, MB-3 Engine
	5 - CastorIVA. Extended Long Tank, RS-27 Engine
	6 - Castor IVA. Extra Extended Long Tank, RS-27 Engine
	7 - GEM. Extra Extended Long Tank, RS-27A Engine
Second Digit	3 - Three Augmentation solid rocket motors
	9 - Nine Augmentation solid rocket motors
Thrid Digit	0 - AJ10-118 (Aerojet)
	1 - TR-201 (TRW)
	2 - AJ10-118K (Aerojet)
Fourth Digit	0 - No Third Stage
	3 - TE-364-3
	4 - TE-364-4
	5 - PAM-D Derivative (STAR 48B)

Table 28. Delta Launch Vehicle Characteristics

		Delta 6925/7925
System height		Up to 38.1m
Stage 1 height		26.1m
Stage 2 height		19.6m
Stage 3 height		6.7m
Payload fairing		2.9m × 8.47m or 3.05m × 7.92m
System gross mass		218,000 kg (6925) 506,000 kg (7925)
SRM gross mass (ground lit, each)		11.7 kg (6925) 13.0 kg (7925)
SRM gross mass (air lit, each)		11.9 kg (6925) 13.1 kg (7925)
Stage 1 gross mass		101.7 kg (6925) 101.9 kg (7925)
Stage 2 gross mass		6,997 kg
Stage 3 gross mass		11.7 kg
SRM propellant mass (each)		101.kg (6925) 11.7 kg (7925)
Stage 1 propellant mass		96,100 kg (6925) 96,000 kg (7925)
Stage 2 propellant mass		6076 kg
Stage 3 propellant mass		10.1 kg
<u>Average thrust</u>		
SRM (SL, each)		427,100 N (6925) 435,000 N (7925)
Stage 1	(SL)	1,020,000 N (6925) 1,043,000 N (7925)
Stage 2	(SL)	42,430 N
Stage 3	(Vac)	66,440 N
<u>ISP</u>		
SRM (SL, each)		237.3 sec (6925) 245.7 sec (7925)
Stage 1	(SL)	263.2 sec (6925) 255.6 sec (7925)
Stage 2	(Vac)	319.4 sec
Stage 3	(Vac)	292.6 sec
<u>Chamber pressure</u>		
SRM		691 psia (6925, 47.7 bar) 817 psia (7925, 56.3 bar)
Stage 1		702 psia (48.4 bar)
Stage 2		827 psia (57.0 bar)
Stage 3		575 psia (39.7 bar)

Table 28. Delta Launch Vehicle Characteristics (continued)

	Delta 6925/7925
Nozzle expansion ratio	
SRM	8.29:1 (6925)
	10.65:1 (7925)
Stage 1	8:1 (6925)
	92:1 (7925)
Stage 2	65:1
Stage 3	54.8:1
Performance	
Geotransfer orbit (28°)	1447 kg (6925)
	1819 kg (7925)
Geosynch orbit	730 kg (6925)
	910 kg (7925)

Sources: Isakowitz (1991) and General Dynamics (1991).

5. Titan

The Titan family of launch vehicles evolved from the Titan I ICBM. The U.S. Air Force's approval of Titan I airframe development in May 1955 led to the award of the development contract to the Martin Company the following October. Following the first test launch in February 1959, the Air Force awarded a contract to Martin for the development of a Titan II missile, which was to use a storable, hypergolic liquid propellant that would not require oxygen. The first successful captive firing of a Titan II took place in December 1961 and was followed by the first test flight in March 1962.

Meanwhile, NASA had considered using the Titan II for its advanced Mercury program early in 1961. Following the December 1961 award to McDonnell Douglas of a contract for 12 Mercury Mark II (Gemini) spacecraft, NASA directed the Air Force to authorize its launch vehicle contractors to begin the work necessary to modify the Titan II for its new manned program.

Man-rating the Titan II for the Gemini program was completed in April 1964 with the successful launch of the unmanned Gemini 1 mission. However, this project suffered delays due to a second-stage combustion instability problem and to the "Pogo effect" of excessive vehicle vibration and oscillation.

As early as September 1961, the Air Force and NASA initiated studies of a standardized, heavy booster to build on the technology of the Titan III A in June 1964, and conducted its first (unsuccessful) test launch in September 1964.

Table 29. Titan Launch Vehicle Characteristics

	Titan III	Titan IV
System height	Up to 47.3 m	Up to 62.2 m
Stage 1 height	24.0 m	26.4 m
Stage 2 height	10.0 m	10.0 m
Payload fairing	4.0 m × 13.0 m or 4.0 m × 16.3 m	5.1 m × 15.2 m 5.1 m × 17.1 m 5.1 m × 20.1 m 5.1 m × 23.2 m 5.1 m × 26.2 m
System gross mass	680,000 kg	860,000 kg
SRM gross mass (each)	247,000 kg	317,000 kg
SRMU gross mass (each)		350,000 kg
Stage 1 gross mass	141,000 kg	163,000 kg
Stage 2 gross mass	38,000 kg	39,600 kg
SRM propellant mass (each)	210,000 kg	273,000 kg
SRMU propellant mass		313,000 kg
Stage 1 propellant mass	134,000 kg	155,000 kg
Stage 2 propellant mass	35,100 kg	35,100 kg
<u>Performance</u>		
Geotransfer orbit (28°)	1850 kg w/PAM-D2 4310 kg w/Transtage and dual carrier 5000 kg with TOS and single carrier	6350 kg with SRM and kick motor 8620 kg with SRMU and kick motor
Geosynchronous orbit (with kick motor)	1360 kg w/single carrier 2500 kg w/dual carrier	2380 kg w/IUS and SRM 4540 kg w/Centaur and SRM 5760 kg w/SRMU
<u>Average thrust</u>		
SRM (each, vac)	6.2×10^6 N	7.0×10^6 N
SRMU (each, vac)		7.5×10^6 N
Stage 1	2.41×10^6 N	2.41×10^6 N
Stage 2	4.62×10^5 N	4.62×10^5 N
<u>ISP</u>		
SRM (vac)	271.6 sec	271.6 sec
SRMU (vac)		285.6 sec
Stage 1	302 sec	302 sec
Stage 2	316 sec	316 sec
<u>Chamber pressure</u>		
SRM	934 psia (64.4 bar)	934 psia (64.4 bar)
SRMU		1260 psia (86.9 bar)
Stage 1	829 psia (57.2 bar)	829 psia (57.2 bar)
Stage 2	827 psia (57.0 bar)	827 psia (57.0 bar)
<u>Nozzle expansion ratio</u>		
SRM	8:1	10:1
SRMU		16:1
Stage 1	15:1	15:1
Stage 2	49:1	49:1

Sources: Isakowitz (1991) and Defense Science Board (1990).

The Titan III consisted of a liquid rocket core that could be combined with strap-on solid rocket motors and a number of upper stages, including the frequently-used Centaur and Transtage vehicles.

NASA's life requirements for interplanetary payloads could not be met by the Atlas-Centaur pairing then available. Further, budget reductions forced the cancellation of a nuclear-powered upper stage and the stretching of the Space Shuttle development schedule. So in February 1968 NASA decided to adopt the Titan III for interplanetary, as well as some earth orbit-type missions. NASA awarded its first Titan study contracts a few months later in June.

The first Titan III mission for NASA involved a Titan III C carrying the ATS 6 satellite into orbit in May 1973. This was followed by a Titan III E test launch in February 1974 that carried a Viking spacecraft model, and the successful launches of two each of the Helios satellite, Viking spacecraft, and Voyager spacecraft between December 1974 and September 1975.

Table 30 characterizes the Titan launch vehicle variants through the current Titan IV and Titan III (commercial Titan) systems. Estimated launch prices for various versions of Titan are listed in Table 31.

Table 30. Titan Launch Vehicles

Model	Description
Titan I	ICBM
Titan II	
Titian II Gemini	Titan II ICBM converted to a man-rated space launch vehicle.
Titan III A	Titan II Gemini with stretched stage 1 and stage 2, and intregal Transtage upper stage.
Titan III B	Titan III A with Agena upper stage in place of Transtage upper stage.
Titan 34B	Titan III A with stretched stage 1.
Titan III C	Titan III A with 5-segment solid rocket motors.
Titan III D	Titan III C with no upper stage.
Titan III E	Titan III C with Centaur upper stage and 4.3 m diameter payload fairing.
Titan 34D	Titan 34B with 51/2 segment solid rocket motor and either Transtage upper stage or Inertial upper stage.
Titan II Space Launch Vehicle	Refurbished Titan II ICBM with 3.0 m payload fairing and up to 10 solid rocket strap-ons.
Titan III (commercial Titan)	Titan 34D with stretched stage 2, enhanced liquid rocket engines, and 4.0 m payload fairing. Compatible with single or dual carriers and uses PAM-D2, Transtage, or TOS upper stage.
Titan IV	Titan 34D with stretched stage 1 and stage 2 and 5.1 m payload fairing. Uses 7 segment Solid Rocket Motor Upgrade, and compatible with either IUS or Centaur upper stage.

Table 31. Estimated Titan Launch Prices

Version	Price (Millions of 1990 Dollars)	Comments
Titan II	$43	No strap-ons
Titan III	$130–150	Upper stage not included
Titan IV	$154	No upper stage
	$214	Titan IV IUS
	$227	Titan IV Centaur

Source: Isakowitz (1991).

IV. UNMANNED SPACECRAFT

A. COST MODELS

We examined six unmanned spacecraft cost models: the NASA Cost Model (Planning Research Corporation 1990a), the Unmanned Space Vehicle Cost Model Sixth Edition (United States Air Force 1988), the Goddard Spacecraft Subsystems Cost Model (Born, Johnson, and Villone 1991), the Jet Propulsion Laboratory (JPL) Unmanned Project Cost Model (Jet Propulsion Laboratory 1991 and 1992), the Institute for Defense Analyses (IDA) Space-based Systems Cost-Estimating Equations (Frazier et al. 1991), and Cost Estimating Methods for Advanced Space Systems developed at the Johnson Space Center (Cyr 1988). The NASA Cost Model was prepared for NASA by Planning Research Corporation (PRC). The Unmanned Space Vehicle Cost Model Sixth Edition (USCM6) was prepared by the Air Force Systems Command Space Systems Division. The Spacecraft Subsystems Cost Model (SSCM) was developed by Goddard Space Flight Center's Resource Analysis Office through PRC. The IDA model was developed for the Defense Information Systems Agency.

1. NASA Cost Model

The NASA Cost Model (NASCOM) is based on the NASCOM database (NASCOM-DB) (see Table 32, which was extracted from the REDSTAR database). The unmanned section of NASCOM-DB contains 42 unmanned spacecraft. NASCOM CERs are based on First Pound Costs which incorporate the spacecraft's weight, and factors to adjust for weight contigency, weight uniqueness, new design, complexity, and specification level. NASCOM contains three separate cost-estimating methods.

Method one is a set of spacecraft-level CERs that are useful for quick estimations. The CERs are segregated for manned planetary spacecraft and manned earth orbital spacecraft. The CERs use the equation form $y = ax^b$, where y is the cost, x is the dry weight, b is the assumed slope, and a is the first pound cost. The first pound costs are provided. Method two is a set of subsystem CERs segregated for unmanned earth orbital and unmanned planetary spacecraft. The same equation is used for these CERs. Method

Table 32. Spacecraft in Databases

IDA Database	USCM6 Database	SSCM Database	NASCOM-DB
AE	AE	AE-3	AE-C
ATS-F	ATS-A/E	AMPTE/CCE	AEM-HCMM
DMSP	ATS-F	ATS-6	AMPTE-CCE
DSCS IIIA	DMSP, BLOCK 5D-1	COVE-ELV	ATS-1(B)
DSCS IIIB	DSCS III	COBE-STS	ATS-2(A)
FLTSATCOM	FLTSATCOM	DE-1	ATS-5(E)
GPS 9-11	GPS 9-11	DE-2	ATS-6(F)
INTELSAT IV	HEAO	ERBS	COBE
INTELSAT V	IDCSP	EUVE	DE-1 (A)
IDCSP	INTELSAT IV	GOES-1	DE-2(B)
MARISAT	INTELSAT V-A	GOES-2	DMSP-5D
NATO III	MARISAT	GOES-3	DSCS II
OSO	NATO III	GOES-4	ERBS
P78-1	OSO	GRO	GPS I
S3	P78	HCMM	GRO
TACSAT	S3	HEAO-1	HEAO-A
TDRSS	TACSAT	HEAO-2	HEAO-B
	TDRSS	HEAO-3	HEAO-C
		HST	HST
		ISEE-1	IDCSP/A
		ISEE-2	INTELSAT III
		ISEE-3	LANDSAT-A
		ISTP	LANDSAT-D
		IUE	LUNAR ORBITER
		LANDSAT-1	MAGELLAN
		LANDSAT-2	MAGSAT
		LANDSAT-3	MARINER 4
		LANDSAT-4	MARINER 6
		LANDSAT-4'	MARINER 8
		MAGSAT	MARINER 10
		NOAA-6 (A)	MODEL 35
		NOAA-B	OSO-8
		NOAA-7(C)	PIONEER 10
		NOAA-D	SCATHA
		NOAA-8 (E)	SMS-1
		NOAA-9 (F)	SURVEYOR
		NOAA-10 (G)	TACSAT
		OSO-8	TIROS-M
		P78-1	TIROS-N
		SAGE	VELA IV
		SME	VIKING LANDER
		SMM	VIKING ORBITER
		SMS-1	
		SMS-2	
		TIROS-M	
		TIROS-N	
		UARS	
		XTE	

three is an analogous technique. Component and subsystem-level contractor costs are provided for the same 42 unmanned spacecraft. Complete descriptions of the three methods can be found in the documentation by Planning Research Corporation (1990a).

2. Unmanned Space Vehicle Cost Model Sixth Edition

Unmanned Space Vehicle Cost Model Sixth Edition (USCM6) is a parametric tool for estimating earth orbiting unmanned spacecraft nonrecurring and recurring costs. Based on twenty years of research activities, the data is from contractors, government procuring organizations, OSD's cost information reports, and commercial spacecraft companies. USCM6 contains cost and technical data on 18 satellite programs including military, NASA, and commercial spacecraft (see Table 32). USCM6 contains subsystem level and component level CERs based on both physical and performance characteristics.

3. Spacecraft Subsystems Cost Model

The Spacecraft Subsystems Cost Model (SSCM) is a parametric cost model based on a database of 48 unmanned spacecraft (see Table 32). It contains a set of subsystem CERs developed using least squares regression with the primary independent variable being subsystem dry weight. Other variables were analyzed, however, weight proved to be the best estimator. There are a total of six subsystems plus an overall system level group.

For each subsystem there are two CERs: one for the protoflight unit and one for the follow-on unit. The protoflight unit includes nonrecurring and recurring costs to produce the first unit. The follow-on unit includes recurring costs only. The CERs are in the form:

$$\text{Cost} = a(\text{weight})^b,$$

where a and b are provided.

4. JPL Unmanned Project Cost Model

The JPL Unmanned Project Cost Model is a performance-based model for new spacecraft designs that use state-of-the-art technology. The JPL model, comprised of both the USCM and NASCOM databases, has over 25 years of maturity. It contains a set of functional subsystem CERs with system and program modifiers. The inputs for these CERs are either performance, or weight, or both. The technical staff defines the model inputs. Two separate CERs are provided for each subsystem: one for Design and Development and one for the Single Equivalent Hardware Unit.

The subsystems modeled are science payload, command and data, radio communications, attitude control, electrical power, mechanical devices, integration, and propulsion. The functional subsystem CERs are stratified by the complexity of the spacecraft design. The system modifiers applied to the CERs are a technology amplifier, a quality factor, an inheritance factor, and a factor based on the number of qualification tests.

There are two modes of operation, performance and weight-based. These results are compared with each other and with the actual costs for other spacecraft.

5. IDA Model

The IDA model is a cost and technology forecasting tool for satellite bus and communications payloads based on cost and technical information for 17 satellite programs (see Table 32). It is a set of spacecraft subsystem and component level parametric equations for nonrecurring hardware and software costs and recurring hardware costs derived by regression analysis. The CERs are in linear and log forms and are both performance and weight-based.

The model forecasted three major satellite design and fabrication trends. First, that digital electronics will experience decreasing costs. Second, manufacturers in the design and development activities will experience learning over time. Third, satellite capabilities in terms of weight and performance will increase over time.

6. Johnson Space Center Model

The JSC model is a parametric cost estimating model for space systems in the conceptual design phase. It is a long-range forecasting tool based on a database of 264 major programs including ground vehicles, ships, aircraft, missiles, and spacecraft. The CER provided is the result of multiple linear regression analysis:

$$\text{Cost} = 0.0000172 Q^{0.5773} W^{0.6569} 58.95^{C} 1.0291^{Y} G^{-0.3485},$$

where $Q = \log_{10}$ total quantity, $W = \log_{10}$ weight, C = culture, Y = initial operational capability year, and G = generation. See the documentation by Planning Research Corporation (1990a) for a further description.

B. PROGRAMS

1. Explorer

The Explorer satellites were a varied collection of spacecraft, ranging from inflatable spheres to windmill-shaped satellites. Their missions were equally varied, including studies of the Earth's environment, astronomical observations, and studies of terrestrial-solar-interplanetary relationships.

Table 33. Explorer Chronology

July 1955	Army Ballistic Missile Agency and Jet Propulsion Laboratory propose a plan for launching a small satellite on a Redstone booster with a Sergeant second stage. U.S. officials announce plays to launch a satellite as part of the International Geophysical Year (IGY).
August 1955	DoD Advisory Group on Special Capabilities (Stewart Committee) selects the Naval Research Laboratory's Vanguard proposal over the Army's Orbiter project for the IGY satellite.
November 1957	DoD officially directs the U.S. Army to proceed with its Explorer program after delays with the Vanguard program.
January 1958	Explorer I, the first successful U.S. satellite, was launched by a Juno I booster.

In particular, Explorer missions included studies of energetic particles (nos. 6, 7, 10, 12, 14, 15, 26); studies of the atmosphere (nos. 9, 17, 19, 32) and the ionosphere (nos. 8, 20, 22 27, 31); studies of micrometeoroids (nos. 13, 16, 23); interplanetary observations (nos. 18, 21, 28, 33, 34, 45); studies of air density (Injun Explorers nos. 24, 25, 39, 40); radio astronomy (no. 38); geodetic studies (nos. 29, 36); gamma ray astronomy (no. 11); and studies of the Sun (nos. 30, 37).

In the constellation of NASA satellites, the Explorer satellites, especially the early satellites, tended to be smaller, simpler, and less expensive than other science satellites. As such, they often performed preliminary surveys and gathered basic data as precursors to more sophisticated missions.

By the time NASA was established in 1958, the U.S. Army Ballistic Missile Agency had already attempted five Explorer missions. By the time of the last Explorer mission in November 1975 the program had subsumed 62 space craft. No single NASA center was responsible for all of the these satellites, although GSFC and LARC were associated with many of them.

The information on the Explorer came from a number of sources. For further information, see Corliss (1967), Ezel (1988), and Rosenthal (1982).

Table 34. Explorer-Class Satellite Programmed Funding History, 1959-68

Year	Funding (millions of 1990 constant dollars)
1959	39.26[a]
1960	76.44[b]
1961	116.24[c]
1962	25.15
1963	177.84
1964	80.53
1965	108.17
1966	87.98
1967	82.21
1968	75.04
1968	75.04
Total	868.86

Note: Included in this table, in addition to Explorer satellites, are funds spent from FY 1959–63 on satellite projects that were listed in the budget estimates under names other than Explorer but that subsequently were flown as Explorers, and some projects that were not flown but were in the Explorer class.

[a] Includes $31,400,000 for Explorer; $3,498,000 for an ionospheric beacon satellite; $1,382,000 for an ionospheric direct measurements satellite; $1,130,000 for an advanced radiation belt satellite; $910,000 for an atmospheric structures satellite; and $942,000 for a radiation belt satellite.

[b] Includes $13,650,000 for Explorer 6; $8,550,000 for Explorer 7; $307,000 for a 3.66-meter sphere; $3,402,00 for a radiation balance experiment; $4,991,000 for an energetic particles satellite; $14,974,000 for an ionospheric beacon satellite; $11,693,000 for an ionospheric direct measurements satellite; $3,402,000 for an atmospheric structures satellite; $13,156,000 for a gamma ray astronomy satellite; $1,355,000 for a Scout micrometeoroid satellite; $753,000 for an air density drag measurements satellite; and $1,830,000 for a fixed-frequency topside sounder.

[c] Includes $18,330,000 for an energetic particles satellite; $11,971 for an ionospheric beacon satellite; $11,400,000 for an ionospheric direct measurements satellite; $20,454,000 for a gamma ray astronomy satellite; $16,650,000 for a Scout micrometeoroid satellite; and $27,968,000 for topside sounders.

Table 35. Physics and Astronomy Explorer-Class Satellite Programmed Funding History, 1969-78

Year	Funding (millions of 1990 constant dollars)
1969	78.68
1970	69.30
1971	92.06
1972	76.18
1973	105.74
1974	97.54
1975	91.14
1976	181.52
1977	67.25[a]
1978	72.21[b]
Total	931.62

[a] Includes $52,133,000 for development and $15,117,000 for mission operations.

[b] Includes $50,125,000 for development and $22,080,000 for mission operations.

Table 36. Explorer Satellite Characteristics

Spacecraft	Launch Date	Weight (kg)
6	8/59	64.4
7	10/59	41.5
8	11/60	40.8
9	2/61	36.3
10	3/61	35.4
11	4/61	43.1
12	8/61	37.6
13	8/61	83.9
14	10/62	40.4
15	10/62	45.4
16	12/62	100.7
17	4/63	185.5
18	11/63	62.6
19	12/63	43.1
20	8/64	44.5
21	10/64	61.7
22	10/64	52.2
23	11/64	133.8
24	11/64	8.6
25	11/64	40.8
26	12/64	45.8
27	4/65	60.8
28	5/65	59
29	11/65	174.6
30	11/65	56.7
31	11/65	98.9
32	5/66	220
33	7/66	93.4
34	5/67	73.9
35	7/67	104.3
36	1/68	208.7
37	3/68	88.5
38	6/68	275.3
39	8/68	9.4
40	8/68	71.2
41	6/69	78.7
42	12/70	81.6
43	3/71	288
44	7/71	115
45	11/71	50
46	7/72	167.8
47	9/72	375.9
48	11/72	92
49	6/73	330
50	10/73	397.2
51	12/73	668
52	6/74	26.6
53	5/75	196.7
54	10/75	675
55	11/75	675
56	12/75	35.3
57	12/75	35.8

2. Tiros Satellite Family (including TOS, ITOS, NOAA)

Project Tiros (Television Infra-red Observation Satellite) was NASA's first, and arguably the first major U.S. meteorological satellite program. Research on weather reconnaissance satellites had been pursued well before the establishment of NASA. RCA had been studying a weather satellite since 1951. However, in 1956 the Army Ballistic Missile Agency awarded RCA a contract to continue this research, and by 1958 the authority for RCA's Project Janus had been transferred to the new Advanced Research Projects Agency (ARPA).

By the time that NASA assumed responsibility for the nation's weather satellite programs in April 1959, the Tiros 1 configuration had emerged from the design process. The successful launch of Tiros 1 in April 1960 marked the start of a series of ten development test flights of Tiros satellites that ended in July 1965 with the flight of Tiros 10.

The Tiros satellites each carried two-camera television systems in addition to assorted radiometers and the first real time, automatic picture transmission (APT) systems. In general, the Tiros satellites collected meteorological data, functioned as testbeds for new hardware, and allowed the evaluation of weather satellite system principles.

The completion of the Tiros series of satellites led to the Tiros Operational System, or TOS. The first TOS satellite, designated ESSA 1 (Environmental Science Services Administration), successfully flew in February 1966. It was followed by eight additional successful TOS satellites, ESSA 2 through 9, the last of which was launched in February 1969. The TOS satellites typically carried the APT television system, although some of the later models carried the advanced vidicon camera system (AVCS) instead, starting with ESSA 3.

The satellites to follow the Tiros and TOS satellites grew in size to accommodate evolving instrument suites. The first of the new satellites was Tiros M satellite, which functioned as an operational prototype of an Improved Tiros Operational System (ITOS). Tiros M, also referred to as ITOS 1, was successfully launched in January 1970.

Tiros M carried two each of the AVCS, the APT system, and a scanning radiometer. This satellite weighed about twice as much as its immediate predecessor, ESSA 9, and was launched about a year after it in January 1970.

Table 37. Tiros/TOS/ITOS/NOAA Chronology

1951	The Rand Corporation contracted with RCA to study the feasibility of using cameras on orbiting satellites.
1956	RCA submitted proposals to the Department of Commerce Weather Bureau and to the military for a television-equipped weather reconnaissance satellite. The Army Ballistic Missile Agency contracted with RCA for work on such a spacecraft called Janus, to be launched by a Jupiter C in the spring of 1958.
February 1958	ARPA assumed responsibility for the television satellite project, with new emphasis being placed on its use as a meteorology satellite.
March 1958	RCA redesigned Janus for use with the Juno II launch vehicle. The satellite effort, as redirected toward a meteorology mission, was called Tiros.
Summer-Winter 1958	RCA's contract with ARPA called for the manufacture of 10 satellites.
April 1959	Project Tiros was transferred to NASA. Goddard Space Flight Center was given management responsibility.
April 1960	Tiros 1 was launched successfully.
October 1960	An interagency meeting was held on the establishment of an operational meteorology satellite system.
June 1961	NASA awarded RCA a letter contract for four Tiros satellites.
February 1963	NASA awarded RCA a letter contract for seven Tiros satellites.
March 1964	NASA and the Weather Bureau reached an agreement on an operational satellite system using an improved Tiros.
July 1964	RCA was awarded a contract for the TOS program.
Late 1965	Goddard awarded RCA a study contract for a second generation TOS.
May 1966	NASA announced that it would negotiate with RCA for a design study of an improved Tiros.
June 1966	Tiros J was canceled and replaced by Tiros M, a new generation system.
November 1966	NASA announced that it would negotiate with RCA for a design of the Tiros M.
April 1967	NASA awarded RCA a contract for Tiros M and three follow-on operational spacecraft.
November 1967	A Tiros M design review was concluded at RCA.
October 1968	Fabrication of Tiros M was completed.
May 1971	The Tiros N project approval document was signed.
June 1974	Goddard initiated a Tiros N design study.
February 1975	The Tiros N request for proposals was issued.
October 1975	NASA awarded a contract to RCA for eight Tiros N-type spacecraft

About six months after being launched, NASA turned over the Tiros M satellite to the National Oceanic and Atmospheric Administration (NOAA), who operated the subsequent second generation Tiros satellites. Five of these satellites were launched successfully and have been alternatively designated with the NOAA nomenclature and the ITOS nomenclature. Two of the satellites in this series did not reach orbit due to launch vehicle failure.

Table 38. Tiros/TOS/ITOS/NOAA Programmed Funding History, 1959-78

Year	Funding (millions of 1990 constant dollars)
1959	5.14
1960	18.61
1961	17.58
1962	37.45
1963	103.93
1964	59.68
1965	20.57
1966	11.83
1967	5.83
1968	38.95
1969	23.48
1970	14.02
1971	11.40
1972	7.25
1973	13.55
1974	37.19
1975	20.14
1976	19.70
1977	26.02
1978	8.46
Total	500.78

In addition to the aforementioned instruments, some NOAA/ITOS satellites carried a variety of other instruments. These included a solar proton monitor, the VHRR (Very High Resolution Radiometer), and the VTPR (Vertical Temperature Profile Radiometer).

In October 1978 NASA launched another Tiros prototype, Tiros N. Where the NOAA/ITOS satellites weighed about 400 kg, the Tiros N spacecraft weighed over 1400 kg, and carried a correspondingly more sophisticated instrument suite. Tiros N was complemented by NOAA 6, which was launched in June 1979. These satellites were the start of a series based on the Block 5D bus developed for the Air Force DMSP spacecraft.

Tiros N, also referred to as NOAA-N, carried several instruments for monitoring radiation and particles in the space environment, a number of sounding units, and the Advanced VHRR.

With regard to the rest of the satellites in the Tiros N series, NOAA 9 carried the Earth Radiation Budget experiment scanner and nonscanner instruments. It was also the first satellite to carry the SBUV/2 ozone mapping instrument. NOAA 10 carried the Sarsat equipment which functions as part of the Cospas/Sarsat search and rescue system.

Table 39. Tiros Family Spacecraft Characteristics

Spacecraft	Launch Date	Weight (kg)	Primary Instruments
Tiros 1 (-A-1)	4/60	122.5	two-camera TV system
Tiros 2 (-B,-A-2)	11/60	127	two-camera TV system
Tiros 3 (-C,-A-3)	7/61	129.3	two-camera TV system, scanning and wide field radiometers, omni-directional radiometer
Tiros 4 (-D,-A-9)	2/82	129.3	same as Tiros 3
Tiros 5 (-E,-A-50)	6/62	129.7	same as Tiros 3
Tiros 6 (-F,-A-51)	9/62	127.5	two-camera TV system
Tiros 7 (-G,-A-52)	6/63	134.7	two-camera TV system, electron temperature probe, omni-directional radiometer
Tiros 8 (-H,-A-53)	12/63	120.2	two-camera TV system, APT system
Tiros 9 (-I,-A-54)	1/65	138.3	two-camera TV system
Tiros 10 (OT-1)	7/65	131.5	two-camera TV system
ESSA 1 (OT-3)	2/66	138.3	two-camera APT TV system
ESSA 2 (OT-2)	2/66	131.5	two-camera APT TV system
ESSA 3 (TOS-A)	11/66	147.4	two-camera APT TV system
ESSA 4 (TOS-B)	1/67	131.5	two-camera APT TV system
ESSA 5 (TOS-C)	4/67	147.4	two-camera APT TV system
ESSA 6 (TOS-D)	11/67	129.7	two-camera APT TV system
ESSA 7 (TOS-E)	8/67	147.7	two-camera APT TV system
ESSA 8 (TOS-F)	1/67	136.1	two-camera APT TV system
ESSA 9 (TOS-G)	2/69	157	two AVCS
ITOS 1 (Tiros M)	1/70	309	two each of AVCS, APT system, scanning radiometer
NOAA 1 (ITOS-A)	12/70	409	same as ITOS 1
ITOS B (launch failure)	11/71	409	two each of AVCS, APT system, scanning radiometer, plus 1 each of Solar Proton Monitor, flat plate radiometer
NOAA 2 (ITOS-D)	11/72	409	VHRR, VTPR, scanning radiometer
ITOS-E (launch failure)	7/73	409	VHRR, VTPR, scanning radiometer, Solar Proton Monitor, SARSAT, MSU SSU, SEM
NOAA 3 (ITOS-F)	11/73	409	same as ITOS-E
NOAA 4 (ITOS-G)	11/74	409	same as ITOS-E
NOAA 5 (ITOS-H)	7/76	409	same as ITOS-E
Tiros N (NOAA-N, Operational Temperature Sounding Satellite)	10/78	1405	TOVS, HRIRS, SSU, MSU, AVHRR, SEM, MEPED, HEPED
NOAA 6	6/79		
NOAA B (failed to achieve orbit)	5/80		
NOAA 7	6/81		
NOAA 8 (NOAA E)	3/83		AVHRR, MSU, SSU, SEM
NOAA 9 (NOAA F)	12/84		AVHRR, MSU, SSU, SEM, ERBE, SARSAT, SBUV/2
NOAA 10 (NOAA G)	9/86		AVHRR, MSU, SSU, SEM, ERBE, SARSAT, SBUV/2
NOAA 11 (NOAA H)	9/88		AVHRR, TOVS, SBUV/2
NOAA 12 (NOAA D)	5/91		AVHRR, HIRS, MSU, SEM, ARGOS, SARSAT

NOAA 12 was the last satellite in the series to be placed into orbit as of the publication of this document, having been placed there in May 1991. A number of additional NOAA satellites have been planned for the future. NOAA 14 (NOAA J), with a planned launch date in 1993, was built to replace NOAA 12. NOAA K through N will be the next generation of NOAA satellites. In the 2000 to 2006 time frame, the NOAA O, P, and Q are planned to be the next generation yet, carrying the contemporary family of advanced sensing instruments.

The Goddard Space Flight Center had the management responsibility for the Tiros family of satellites and RCA has been the prime contractor throughout the program until the acquisition of its Astro-Electronics unit by GE. Now, GE's Astro-Space unit has been the prime contractor for NOAA 11 and subsequent spacecraft through NOAA N.

The information on the Tiros family of satellites came from a number of sources. For further information, see Ashby (1964), Ezell (1988), Forecast International (1991a), Rosenthal (1982), and Wilson (1991).

3. Ranger

The Ranger program consisted of nine spacecraft that were intended for lunar exploration. The first two Rangers, designated Block I, were to achieve lunar near misses or probes, while the remaining Rangers were to achieve a lunar impact. The Block I Rangers carried instrumentation to measure radiation, solar emissions, and magnetic fields in the cis-lunar environment. They were also to serve as test vehicles for the new, hexagonally-shaped, solar-powered spacecraft design. In addition to other scientific instruments, the impact-Rangers carried television camera systems to obtain pictures of the lunar surface. The first Ranger spacecraft was launched in August 1961, while the last, Ranger 9, flew in March 1965.

The Jet Propulsion Lab (JPL) managed the Ranger program for NASA. Ford Motor Company's Aeronautics Division manufactured five lunar capsule subsystems for the program, commencing with Ranger 3. The Radio Corporation of America's Astro-Electronics Division produced the television camera system for all Rangers so equipped.

Table 40. Ranger Chronology

April 1958	JPL's Functional Design Group was established to study the possibilities for a 160 kg spacecraft capable of a Mars mission.
February 1959	NASA Headquarters and JPL officials established management responsibilities for the Vega launch vehicle program, and proposed payloads for lunar and deep space missions.
December 1959	The Vega launch vehicle program was canceled. JPL was directed to establish a post-Vega lunar and interplanetary flight program. Emphasis was given to high resolution photographic goals.
January 1960	NASA selected eight experiments for the first near-lunar missions. The first three Ranger missions were scheduled for February through August 1961.
February 1960	NASA Headquarters gave JPL permission to proceed with the Ranger program.
March 1960	JPL awarded study contracts for Ranger design. RCA received a letter contract for the post-Block I television camera system.
April 1960	JPL awarded Ford a contract for five rough-landing capsules ($4.8 million TY, contract value).
June 1961	Plans for Block III [illegible]nger follow-on missions were delivered.
August 1961	Ranger 1 was l[illegible] but did not achieve intended orbit.
June 1962	Initial planni[illegible] [illegible]arted for a Block IV Ranger spacecraft.
October 1962	A Ranger boar[illegible] [illegible] inquiry was established.
February 1963	Block III and Block IV missions were reprogrammed to impacting-photography objectives only.
December 1963	NASA headquarters directed JPL to terminate all activities on impact missions beyond Block III. Soft-landing missions were not explicitly canceled.

Table 41. Ranger Programmed Funding History, 1960-66

Year	Funding (millions of 1990 constant dollars)
1960	117.66
1961	262.92
1962	355.84
1963	481.38
1964	157.20
1965	55.36
1966	4.73
Total	1,435.09

All Ranger spacecraft had the same structural design, a hexagonal base with two rectangular solar arrays, a pointable high-gain antenna, and an omni-directional low-gain antenna.

The first two Ranger missions to put the spacecraft into highly eliptical earth orbit failed due to launch vehicle malfunction. However, while the Block II Rangers 3 and 4

were boosted to lunar impacts, they failed to provide telemetry, and thus failed in their missions. The last Block II Ranger missed the Moon by 725 km, and so also failed in its mission.

The Block III Ranger 6 only carried the television camera system in an effort to simplify the mission and the demands on the spacecraft. However, Ranger 6 also failed to transmit data before impact.

Subsequent program reviews and changes led to the three successful Ranger missions that concluded the program.

Table 42. Ranger Spacecraft Characteristics

Spacecraft	Launch Date	Weight (kg)	Diameter (m)	Height (m)
Ranger 1	8/61	306.18	1.5	3.6
Ranger 2	11/61	306.18	1.5	3.6
Ranger 3	1/62	—	1.5	3.6
Ranger 4	4/62	331.12	1.5	3.6
Ranger 5	10/62	342.46	1.5	3.6
Ranger 6	1/64	364.69	1.5	3.6
Ranger 7	7/64	365.60	1.5	3.6
Ranger 8	2/65	366.87	1.5	3.6
Ranger 9	3/65	366.87	1.5	3.6

The information on the Ranger came from a number of sources. For further information, see Ezell (1988, vol. II), Hall (1971), Hall (1977), and Rosenthal (1982).

4. Surveyor

The Surveyor program consisted of seven spacecraft that were intended to land on the moon and collect data, in direct support of the Apollo program and the goal of a manned lunar landing. Equipped with a television camera, a sampling scoop, magnetic footpads, and an alpha particle-scattering instrument, each Surveyor was to provide Apollo with information on the lunar crust and its bearing limits, soil, magnetic properties, and radar and thermal reflectivity.

Early plans for the Surveyor spacecraft envisioned it as a combined orbiter and lander that would carry a number of instruments for lunar exploration. However, by mid-1962 a number of events had occurred that changed the course of the program. According

to Ezell (1988), development problems with the proposed launch vehicle, the Centaur upper stage (early failures with the Ranger program) and the urgent demands of the Apollo program for lunar surface data, combined with weight constraints, had two consequences. First, the more general scientific mission gave way to the focus on Apollo-specific data requirements. Second, the orbiter portion of the Surveyor design was dropped from the program. The objectives of the canceled orbiter were taken over by the newly initiated Lunar Orbiter program.

Table 43. Surveyor Chronology

May 1960	NASA approved the Surveyor launch program, which would consist of an orbiter to collect photographs and a lander to perform surface exploration.
July 1960	Surveyor study contracts were awarded, with JPL providing design requirements.
January 1961	NASA selects Hughes Aircraft to build seven Surveyor landers. The first launch was scheduled for August 1963.
March 1961	Hughes Aircraft received a letter contract to build seven Surveyor landers.
May 1962	The first Atlas-Centaur test launch was unsuccessful.
Mid-1962	The Surveyor program was reconfigured to include only the orbiter. The first Surveyor launch was postponed.
Early 1963	Initial testing of the first proof test model was completed.
December 1964	A Surveyor model was successfully launched on an Atlas- Centaur launch vehicle.
August 1965	A Surveyor model was successfully launched into an elliptical Earth orbit by an Atlas-Centaur launch vehicle in order to simulate a lunar transfer orbit.
May 1966	The Surveyor spacecraft accomplished a soft-landing test under its own power.
May 1966	Surveyor 1 was successfully launched.

Table 44. Surveyor Programmed Funding History, 1959–78

Year	Funding (millions of 1990 constant dollars)
1961	41.15
1962	219.54
1963	359.81
1964	366.74
1965	410.38
1966	495.13
1967	360.62
1968	141.24
Total	2,394.61

The seven Surveyor landers were essentially identical in design. Each spacecraft consisted of a triangular aluminum frame containing two equipment compartments. Three legs equipped with shock absorbers and footpads provided structural support for the soft lunar landing. The spacecraft's three venier engines and a single retrocket provided the power and control for the descent to the lunar surface.

The first Surveyor spacecraft was launched successfully on May 30, 1966 and successfully landed on the moon a few days later on June 2. The last spacecraft, Surveyor 7 was launched successfully in January 1968. Altogether, all but two of the Surveyors succeeded in their mission.

The NASA Headquarters Office of Lunar and Planetary Programs managed the Surveyoı program, but the Jet Propulsion Laboratory was the cognizant center for the program. Hughes Aircraft was the prime contractor for spacecraft fabrication.

Table 45. Surveyor Spacecraft Characteristics

Spacecraft	Launch Date	Weight (kg)	Height (m)
Surveyor 1 (Surveyor-A)	5/66	995.2	3
Surveyor 2 (Surveyor-B)	9/66	995.2	3
Surveyor 3 (Surveyor-C)	4/67	997.9	3
Surveyor 4 (Surveyor-D)	7/67	1,037.4	3
Surveyor 5 (Surveyor-E)	9/67	1,006.0	3
Surveyor 6 (Surveyor-F)	11/67	1,008.3	3
Surveyor 7 (Surveyor-G)	1/68	1,040.1	3

The information on the Surveyor came from a number of sources. For further information, see Ezell (1988, vol. II) and Rosenthal (1982).

5. Syncom

The Syncom program consisted of three satellites developed with the objectives of obtaining experience using communications in 24-hour synchronous orbit, flight-testing new techniques for satellite control, and evaluating transportable ground facilities. The program nominally followed the Echo and commercial Telstar programs. It also nominally followed the Relay satellite program, which successfully demonstrated that a satellite could be used as an active microwave repeater. Syncom 1 was launched into orbit in February 1963. It was followed there by Syncom 2 in July 1963 and by Syncom 3 in August 1964.

Although Syncom 1 was lost because of rough handling by the launcher's apogee kick motor, the program was considered to be successful in achieving its objectives.

By late 1964, NASA had completed its slate of tests and demonstrations with the operating Syncom satellites. Since the U.S. Army had canceled a similar but more ambitious program a year earlier, NASA transferred Syncom to the Department of Defense in April 1965 to support their own satellite communications program.

The Goddard Space Flight Center was the cognizant NASA center for the Syncom program throughout. Hughes Aircraft was the spacecraft prime contractor, as well as the originator and prime mover/shaker behind the idea of pursuing the program.

Table 46. Syncom Chronology

September 1959	Hughes Aircraft informally proposed its Syncom spacecraft to NASA.
February 1960	Hughes Aircraft formally proposed its Syncom spacecraft to NASA.
June 1961	DoD announced its support of a NASA synchronous-orbit communications satellite project.
August 1961	Goddard personnel prepared a preliminary project development plan in coordination with the U.S. Army Advent Management Agency for a Syncom project.
February 1963	Syncom 1 was launched.

Table 47. Syncom Programmed Funding History, 1962–65

Year	Funding (millions of 1990 constant dollars)
1962	70.75[a]
1963	70.53
1964	13.02
1965	0.84
Total	155.14

[a] Includes $1,122,000 (TY) for an Advanced Syncom study.

Table 48. Syncom Spacecraft Characteristics

Spacecraft	Launch Date	Weight (kg) (including apogee kick motor)
Syncom 1 (A)	2/63	68
Syncom 2 (B)	7/63	66.7
Syncom 3 (C)	8/64	65.8

The information on the Syncom spacecraft came from a number of sources. For further information, see Ezell (1988, vol. II), Martin (1984), Morse (1964), and Rosenthal (1982).

6. Nimbus

Nimbus was NASA's second generation meteorology satellite program following the first generation Tiros program. NASA launched eight Nimbus spacecraft altogether between August 1964 and October 1978. This total includes the third spacecraft, Nimbus B, which was destroyed following launch vehicle failure. Although the Environmental Science Services Administration used Nimbus data extensively, several Nimbus spacecraft were always research platforms for the evaluation of new instruments and data collection techniques. Early plans to operationalize the Nimbus system, as had been done with Tiros, ultimately did not come to fruition.

One of the first public descriptions of the new meteorology spacecraft was made by NASA at Congressional authorization hearings and at supplementary appropriations hearings in April 1959. The plans for the Nimbus spacecraft made it a more ambitious venture than its contemporary Tiros spacecraft (Ezell 1988, vol. II).

> The spacecraft's stabilization system would be designed to give the flight team greater control over the spacecraft's position, and thereby, over the readings and photographs Nimbus would take. In addition to automatic picture transmission and advanced vidicom camera systems that could provide very high-quality cloud cover photographs, Nimbus spacecraft would be equipped with high-resolution and medium-resolution radiometers for nighttime infrared reading, which would give meteorologists information on heat retention on a global scale. Mapping water vapor and stratosphere temperature patterns also would be made possible with data returned by Nimbus. Rotating solar paddles, although they malfunctioned on Nimbus 1, provided enough storable energy to power the spacecraft's instruments for nighttime use.

Project Nimbus fell behind schedule and overran its budget. A horizontal scanner, which would allow the spacecraft to be operated in sun-synchronous orbit, and weight gains were the causes of the spacecraft's major problems.

Payloads evolved considerably over the course of the program and each of the later Nimbus spacecraft were tailored to varying mission objectives. In particular, Nimbus 3 and Nimbus 4 collected data yielding vertical profiles of the temperatures in the atmosphere and information on the global distribution of ozone and water vapor. In addition, Nimbus 4 demonstrated the feasibility of determining wind velocity fields by accurately tracking balloons.

Table 49. SMS Chronology

April 1959	NASA described an advanced meteorology satellite research and development project at FY 1960 Congressional authorization hearings and at FY 1959 supplementary appropriation hearings.
August 1959	A Nimbus research and development program was approved by NASA Headquarters.
June 1960	The Weather Bureau Panel on Observations over Space Data Regions issued a report suggesting the need for a research and development satellite beyond Tiros.
Fall 1960	NASA issued a request for proposals for the Nimbus spacecraft design.
December 1960	NASA awarded RCA a contract for the development and fabrication of an advanced vidicom camera system.
February 1961	NASA selected GE as contractor for the fabrication and systems integration of two Nimbus spacecraft.
April 1961	The Panel on Operation Meteorological Satellites recommended expanding the Nimbus research and development project into the Nimbus Operational System (NOS), a joint project by NASA and the Weather Bureau.
November 1961	A preliminary project development plan for Nimbus was prepared at NASA's Goddard Space Flight Center.
January 1962	NASA and the Weather Bureau signed an agreement providing for implementation of NOS. The Weather Bureau approved the preliminary Nimbus project development plan.
December 1962	The Weather Bureau reprogrammed funds from NOS to TOS.
July 1963	The Nimbus project development plan was revised to incorporate DoD-Weather Bureau recommendations.
September 1963	DoD and the Weather Bureau advised the Bureau of the Budget that NASA's research and development program for meteorology satellites should be placed under their control. The Weather Bureau advised NASA that it was withdrawing from NOS as of October.
October 1963	NASA Headquarters approved a revised Nimbus project development plan.
August 1964	Nimbus 1 was launched successfully, but ceased operating in September because of malfunctions.
June 1865	The Nimbus project development plan was revived to reflect the cancellation of NOS and the operation of a second Nimbus mission.
Early 1968	Congress approved a follow-on Nimbus program (E, F).
June 1968	NASA Headquarters approved a replacement for Nimbus B.
November 1968	Congress cut $6.5 million (TY) from the Nimbus budget, forcing the agency to modify its plans.
January 1969	Goddard released a request for proposals for a Nimbus spacecraft. A project approval document for Nimbus E and Nimbus F was approved at NASA Headquarters.
May 1970	Goddard awarded GE a contract for the fabrication of the Nimbus spacecraft. The contract made definite in June.
February 1972	Funds were reallocated from Nimbus to ERTS due to budgetary constraints.
August 1973	GE presented a low-cost Nimbus G spacecraft development plan to NASA Headquarters.
November 1974	Goddard awarded GE a contract for Nimbus G development.

Table 50. Project Nimbus Programmed Funding History, 1960–78

Year	Funding (millions of 1990 constant dollars)
1960	10.85
1961	74.22
1962	133.97
1963	154.80
1964	216.16
1965	80.26
1966	106.75
1967	110.16
1968	144.24
1969	128.76
1970	103.18
1971	88.01
1972	61.10
1973	91.84
1974	74.97[a]
1975	75.99
1976	46.06
1977	34.25
1978	27.05[b]
Total	1,762.62

[a] Includes $48,790,000 for Nimbus 5 and F, and $26,180,000 for Nimbus G.

[b] Includes $1,856,700 for Nimbus extended operations.

Table 51. Nimbus Family Spacecraft Characteristics

Spacecraft	Launch Date	Weight (kg)	Primary Instruments
Nimbus 1 (-A)	8/64	376.5	APT TV system, AVCS, HRIR
Nimbus 2 (-C)	5/66	413.7	APT TV system, AVCS, HRIR, MRIR
Nimbus 3 (-B2)	4/69	571	MRIR, IDCS, SIRS, IRIS, MUSE,
Nimbus 4 (-D)		571	IDCS, SIRS, MUSE, IRLS, IRIS, BUV, FWS, SCR THIR
Nimbus 5 (-E)	12/72	772	SCR, THIR, ITPR, NEMS, ESMR, SCMR
Nimbus 6 (-F)	6/75	585	THIR, ESMR, SCAMS, HIRS, TWERLE, ERBE, LRIR, PMR, T&DRE
Nimbus (-G)	10/78	987	THIR, ERBE, LIMS, SAMS, SAM II, SBUV/TOMS, SMMR, CZCS

Nimbus 5 provided improved thermal maps of the earth. Nimbus 6 monitored Earth environmental conditions, including sea ice cover and rainfall. Finally, Nimbus 7, also referred to as the "Air Pollution and Oceanographic Observing Satellite," collected data on the oceans, on solar and earth radiation, on pollutants, and on upper atmosphere characteristics.

The Goddard Space Flight Center had the management responsibility for the Nimbus satellites and GE was the prime contractor throughout the program.

The information on the Nimbus came from a number of sources. For further information, see Ezell (1988), Rosenthal (1982), and Wilson (1991).

7. Orbiting Geophysical Observatory

The Orbiting Geophysical Observatory (OGO) program consisted of six earth-orbiting platforms that were equipped with instruments to conduct studies of the earth's atmosphere and magnetosphere, interplanetary space, and earth-sun relationships. The series of OGO launches commenced in September 1964 with OGO 1 and ended in June 1969 with OGO 6.

Table 52. OGO Chronology

April 1959	An orbiting observatory was recognized as a long-range flight project by NASA's Office of Space Science, for the purpose of measuring particle flux, solar radiation, and magnetic and electric fields.
Mid-1960	Goddard Space Flight Center personnel did preliminary design work on a new-generation satellite with a standard structure into which different experiments could be integrated Formosan to mission.
August 1960	A conference was held for companies interested in building the 450 kg-class OGO satellite.
December 1960	NASA selected STL and issued a letter contract to proceed with preliminary studies for three OGO spacecraft ($15 million TY).
April 1961	NASA and STL agreed on a 400 kg box-like structure for OGO with removable solar panels and extendible booms.
August 1962	TRW received a definitive contract for OGO.
April 1964	Contract negotiations for a fourth and fifth OGO satellite.
September 1964	OGO 1 launched.
January 1966	Contract negotiations for a sixth OGO satellite.

The OGO program was managed out of NASA Headquarters. The original engineering specifications were prepared at Goddard Space Flight Center, which was the cognizant NASA Center throughout the operational production and operational phases of the program. Space Technology Laboratories (STL) was selected to be the OGO prime

contractor for the first spacecraft. TRW subsequently acquired STL and was the prime contractor for the remaining OGO spacecraft.

The OGO spacecraft represented a departure from the NASA design philosophy that governed earlier space science satellite programs. These predecessors were tailored to suit the available launch vehicles and the instruments required for the investigations they would carry.

Table 53. OGO Programmed Funding History, 1960-69

Year	Funding (millions of 1990 constant dollars)
1960	2.41
1961	31.26
1962	144.34
1963	214.82
1964	222.36
1965	152.25
1966	133.51
1967	111.74
1968	85.87
1969	52.93
Total	1,151.49

During the 1959-60 time frame engineers at the Goddard Space Flight Center suggested that a standardized satellite design would prove a better way of doing business. Standardization would eliminate repeated design efforts for new research programs and would profit from the associated economies of scale in production.

Under the so-called "streetcar" design principal, the OGO spacecraft were designed independently of specific missions and specified to be large enough to carry twenty or more experiments. Adding booms and antenna to the spacecraft would add to its capabilities. Three-axis stabilization of the OGO spacecraft was intended to accommodate investigations that demanded precise orientation for extended periods. However, the first five OGO satellites suffered attitude control problems and the spacecraft spun about their axes, seriously incapacitating many of the payload experiments. Theses problems were corrected in OGO 6, which has been considered to be the most successful satellite in the series.

The information on the OGO program came from several sources. For further information, see Corliss (1967), Ezell (1988), Jackson and Jackson (1975), and Rosenthal (1982).

Table 54. OGO Satellite Characteristics

Spacecraft	Launch Date	Weight (kg)	Dimensions (m) (Excluding booms, solar panels and other antennas)
OGO 1 (OGO-A)	10/64	487.0	0.9 × 0.9 × 1.8
OGO 2 (OGO-C)	11/65	520.0	0.9 × 0.9 × 1.8
OGO 3 (OGO-B)	6/66	515.0	0.9 × 0.9 × 1.8
OGO 4 (OGO-D)	7/67	562.0	0.9 × 0.9 × 1.8
OGO 5 (OGO-EB)	3/68	611.0	0.9 × 0.9 × 1.8
OGO 6	6/69	544.3	1.7 × 0.8 × 1.2

8. Orbiting Solar Observatory

The Orbiting Solar Observatory (OSO) program consisted of eight earth-orbiting platforms that were equipped with instruments to measure solar radiation, X-rays, gamma rays, and dust particles. The series of OSO launches commenced in March 1962 with OSO 1 and ended in June 1975 with OSO-8. The OSO program was managed out of NASA Headquarters from its inception in 1959, but Goddard Space Flight Center was responsible for individual flight projects. Ball Brothers developed and manufactured the OSO spacecraft.

Table 55. OSO Chronology

April 1959	Precision solar measurements from a space-borne platform were included among NASA's immediate space science flight program objectives.
August 1959	An OSO was included in an "Office of Space Sciences Ten Year Program" document as one of the solar physics projects underway at the Goddard Space Flight Center. The first launch was tentatively scheduled for December 1960. Ball Brothers had already been contracted with for a preliminary engineering study.
October 1959	First contract with Ball Brothers for OSO instrumentation.
March 1962	OSO 1 launched successfully.
August 1962	NASA awarded three study contracts for the design of a new solar observatory-type spacecraft.
April 1964	OSO-B damaged in launch vehicle accident. Some parts were salvaged for OSO-B2.
April 1965	NASA contracted with Ball Brothers to manufacture two additional OSOs ($9.6 million).
August 1965	After failing to place OSO-C into orbit, NASA contracted withal Brothers for an additional three spacecraft, to bright total procurement to eight.
December 1965	An advanced OSO program was canceled due to budgetary considerations.
December 1970	NASA awarded Hughes Aircraft a contract for OSOs I-K, but deferred activities on OSO J and K in March 1972 due to budgetary considerations.

All OSOs consisted of two main structural sections. A wheel-like structure consisted of nine wedge-shaped compartments, five of which carried experiments. A fan-

shaped array carried silicon solar cells, as well as experiments requiring a fixed orientation with respect to the Sun.

All OSO spacecraft were also three-gimbaled designs with their wheels spun to provide gyroscopic stabilization and to accommodate scanning scientific instruments. For this purpose the first six spacecraft used three spheres that carried pressurized hydrogen fixed to deployable arms. However, OSO 7, which was larger than its predecessors, used a mechanically-simplified fixed-ballast system.

Although the OSOs enabled scientists to collect hitherto unavailable solar astronomy data, the platforms proved to be small and less sophisticated as research goals expanded. NASA proposed an advanced OSO in 1962 which would carry larger instruments with improved sensor resolution. Budget cuts, however, forced the cancellation of this program.

The information on the OSO program came from a number of sources. For further information, see Corliss (1967), Ezell (1988), NASA (1965), and Rosenthal (1982).

Table 56. OSO Programmed Funding History, 1959-78

Year	Funding (millions of 1990 constant dollars)
1959	1.57
1960	11.22
1961	22.85
1962	32.21
1963	59.08
1964	116.37
1965	83.25
1966	90.15
1967	45.59
1968	48.50
1969	55.92
1970	54.98
1971	60.33
1972	62.70
1973	65.12
1974	37.97
1975	11.56
1976	8.87
1977	2.22
1978	2.68
Total	873.14

Table 57. OSO Satellite Characteristics

Spacecraft	Launch Date	Weight (kg)	Fan or Sail/Wheel Diameter (m)	Wheel/Overall Height (m)
OSO 1 (OSO-A)	3/62	199.6	1.12/1.12	0.23/0.95
OSO 2 (OSO-B2)	2/65	247.2	1.12/1.12	0.23/0.95
OSO 3 (OSO-E)	3/67	284.4	1.12/1.12	0.23/0.95
OSO 4 (OSO-B2)	10/67	276.7	1.12/1.12	0.23/0.95
OSO 5	1/69	288.5	1.10/	/0.95
OSO 6	8/69	288	1.10/	/0.95
OSO 7	9/71	637	1.4/	/2.0
OSO 8	6/75	1052	2.1/1.52	/3.25

9. Orbiting Astronomical Observatory

The Orbiting Astronomical Observatory (OAO) program consisted of three earth-orbiting platforms that were equipped with telescopes, photometers, and other instruments for astronomical observation. The series of OAO launches commenced in April 1966 with OAO 1 and ended in August 1975 with OAO 3. The deployment of OAO B, originally designated OAO 3, failed. The subsequent OAO 3 spacecraft was its replacement in the program. In addition, OAO 1 failed after one and a half days in orbit due to battery failure, resulting in a redesign of subsequent spacecraft.

Table 58. OAO Chronology

April 1959	Stable orbiting platforms with telescopes to make astronomical observations were proposed as part of the space sciences long- range flight program.
December 1959	An OAO project briefing was held at NASA Headquarters for potential industry participants.
October 1960	NASA selects Grumman Aircraft's OAO proposal submission ($23 million TY, contract estimate).
June 1964	NASA ordered a third OAO from Grumman and took an option for two additional spacecraft ($20 million TY, contract estimate for one spacecraft).
April 1965	Grumman given a go-ahead to convert its prototype OAO into a flight-ready spacecraft, to be designated OAO-A2.
May 1965	Grumman awarded a contract for a fourth OAO.
April 1966	OAO 1 launched successfully but failed one and one half days later. As a result of redesign, OAO-2 flight date slipped from late 1967 to late 1968.

The OAO program was managed out of NASA Headquarters. The original engineering specifications were prepared at Ames Research Center, but Goddard Space Flight Center eventually received technical management authority for the flight projects. Grumman Aircraft was the program's prime contractor.

Table 59. OAO Programmed Funding History, 1960–77

Year	Funding (millions of 1990 constant dollars)
1960	2.08
1961	43.59
1962	214.42
1963	212.74
1964	184.70
1965	163.74
1966	105.52
1967	124.95
1968	191.61
1969	147.35
1970	126.08
1971	82.70
1972	45.17
1973	18.18
1974	6.92
1975	6.18
1976	6.40
1977	4.35
Total	1,6786.68

Table 60. OAO Satellite Characteristics

Spacecraft	Launch Date-Failure Date	Weight (kg)	Dimensions (m) (Solar Panels Not Extended)
OAO 1	4/66-4/66	1769.0	3.1 × 5.2
OAO 2	12/68-2/73	1995.8	3.1 × 5.2
OAO B	11/70-(n/a)	2106.0	2.13 × 3.0
OAO 3	8/72- /80	2200.0	2.13 × 3.0

All OAOs were octagonal in shape and equipped with solar paddles. They were constructed of aluminum and had a hollow cylindrical central tube in which experiments were housed. The spacecraft was designed to point in any direction with an accuracy of one minute of arc during the observation of any individual star. However, the accuracy could be increased to 0.1 second of arc using the sensors of the payload experiments.

The information on the OAO porgram came from several of sources. For further information, see Corliss (1967), Ezell (1988), NASA (1962), Rosenthal (1982), and Rudney (1971).

10. Applications Technology Satellite

The Applications Technology Satellite (ATS) program consisted of six spacecraft whose objective was to investigate and flight test technological developments common to a number of satellite applications.

Table 61. ATS Chronology

February 1962	Hughes Aircraft proposed an advanced Syncom to NASA.
June 1962	A project approval document was issued for the study of an advanced synchronous orbit satellite A project development plan for an advanced stationary communications was prepared at Goddard.
September 1963	Goddard supported an advanced Syncom in recommendations to NASA headquarters.
Fall 1963	NASA terminated its plans for an advanced Syncom flight project. Personnel at Goddard, Hughes, and NASA Headquarters studied ways to reorient the advanced Syncom design to include more areas of research.
February 1964	A project approval document was issued for an Advanced Technology Satellite, later renamed the Applications Technology Satellite.
May 1964	Hughes received a letter contract from NASA for the development and fabrication of the ATS spacecraft.
May 1966	Goddard awarded contracts for feasibility studies (Phase A) for an advanced ATS (-F and -G).
December 1966	ATS 1 was launched.
April 1970	NASA awarded the advanced ATS contract to GE. Fairchild Industries protested on the basis of submission irregularities.
July 1970	GAO advised NASA to reopen the bidding.
September 1970	NASA reversed its decision and awarded the ATS contract to Fairchild Industries.
Spring 1972	NASA postponed the ATS F launch from spring 1973 to spring 1974 because of cost overruns and other problems with contract management.
January 1973	NASA canceled the ATS G mission due to budgetary considerations. NASA mothballed the ATS G spacecraft in November 1974.
May 1974	NASA launched ATS 6 (F).

Table 62. ATS Spacecraft Characteristics

Spacecraft	Launch Date	Weight (including adapter for 1-4, kg)	Cylindrical Dimensions (m)
ATS 1 (A)	12/66	737.1	1.47 × 1.52
ATS 2 (B)	4/67	323.4	1.83 × 1.42
ATS 3 (C)	11/67	714.0	1.47 × 1.37
ATS 4 (D)	8/68	834.6	1.83 × 1.42
ATS 5 (E)	8/69	431.0	1.4 diameter × 1.8 long
ATS 6 (F)	5/74	1336.0	8.51 long

Table 63. ATS Programmed Funding History, 1963–78

Year	Funding (millions of 1990 constant dollars)
1963	47.09
1964	90.97
1965	124.49[a]
1966	169.32[b]
1967	140.92[b]
1968	112.69[b]
1969	100.01
1970	147.60
1971	84.62
1972	165.73
1973	169.61
1974	50.58[c]
1975	—[d]
1976	—
1977	—
1978	7.84[e]
Total	1,411.47

[a] Includes supporting research and technology funds for Applications Technology Satellites and communications.

[b] In the FY 1968–70 budget estimates, Applications Technology Satellites were funded as part of OSSA's space applications program.

[c] Includes $2,380,000 (TY) for experiments coordination and operations support for ATS F and Communications Technology Satellite (CTS).

[d] It was estimated in the FY 1976 budget estimate that $6,200,000 (TY) would be programmed for ATS in FY 1975; the category was dropped in the FY 1977 estimate.

[e] For communications follow-on data analysis and operations for ATS 6 and CTS.

The program arose from the Advanced Syncom project, which was to accomplish communications and meteorology tasks for NASA from a synchronous orbit. Following the program's cancellation, satellite specialists at Hughes Aircraft, Goddard Space Flight Center, and NASA Headquarters sought ways to integrate their ideas for communications, meteorology, and navigation/traffic control satellites into a single-spacecraft package. The project approval document for an Advanced Technology Satellite, later renamed Applications Technology Satellite, followed shortly thereafter.

Table 64. Applications Technology Satellite Experiments

Experiment	Spacecraft A	B	C	D	E
Microwave Communications	X	X	X	X	X
VHF Communications	—	X	X	—	—
WEFAX (see meteorology experiment)	—	—	—	—	—
Ground to Aircraft	—	—	—	—	—
Propagation Effect of VHF	—	—	—	—	—
Navigation Systems	—	—	—	—	—
STADAN Calibration	—	—	—	—	—
Millimeter Wave Communication	—	—	—	—	X
Meteorological Experiments	—	—	—	—	—
Spin Scan Cloud Cover Experiment (SSCCE)	—	—	—	—	—
Black and White	—	X		—	—
Color	—	—	X	—	—
Advanced Videcon Camera System (AVCS)	X	—	—	—	—
WEFAX	—	X	X	—	—
Image Dissector Camera System (IDCS)	—	—	X	—	—
OMEGA Position Location Experiment (OPLE)	—	—	X	—	—
Image Orthican Day/Night Camera		—	—	X	—
Gravity Gradient	X		—	X	X
Antenna	—		—	—	—
Phased Array	—	X		—	—
Mechanically Despun	—		X	—	—
Nutation Sensor	—	X	X	—	—
Subliming Solid Jet	X	—	—	X	X
Hydrazine Rocket	—	—	X	X	X
Resistojet	—	X	X	X	X
Ion Engine	—	—	—	X	X
Reflectometer	—	—	X	—	—
Self-Contained Navigation System	—	—	X	—	—
Environmental Measurements Experiments	—	—	—	—	—
Omnidirectional Particle Telescope (UCSD)	X	—	—	—	X
Omnidirectional Particle Telescope (Aerospace)	—	X	—	—	—
Particle Detector (BTL)	X	—	—	—	—
Proton/Electron Spectrometer (U. of Minn.)	X	—	—	—	—
Solar Cell Damage (GSFC-Dr. Waddell)	X	X	—	—	—
Thermal Coatings (GSFC-J. Triolo)	X	X	—	—	—
Ion Detector (Rice University)	—	X	—	—	—
Magnetometer (UCLA)	—	X	—	—	—
VLF Detector (BTL)	X	—	—	—	—
Cosmic Radio Noise (GSFC-Dr. Stone)	X	—	—	—	X
Electric Field Measurement (GSFC-Dr. Aggson)	X	—	—	—	X
Trapped Radiation Detector (UCB)	—	—	—	—	X
Proton/Electron Detector (Lockheed)	—	—	—	—	X
Spacecraft Charge Measurement (GSFC-Dr. Aggson)	—	—	—	X	X

Notes: BTL=Bell Telephone Laboratories; STADAN=Satellite Tracking and Data Acquisition Network; UCB=University of California at Berkeley; UCSD=University of California at San Diego; WEFAX=weather facsimile.

Source: Ezell, L. N., *NASA Historical Data Books*, Volume II, NASA SP-4012, 1988.

The first ATS satellite was successfully launched in December 1966, and was followed by the remaining five satellites through May 1974. The success of the ATS program was compromised throughout by launch vehicle failures. In the case of ATS 2 and ATS 4, launch vehicle malfunctions prevented the spacecraft from reaching useful orbits. In the case of ATS 5, ground controllers were able to rescue the satellite from the effects of a launch vehicle failure, allowing some secondary experiments to be performed.

The Goddard Spaceflight Center was the cognizant NASA center for the ATS program. Hughes Aircraft designed and fabricated all of the ATS spacecraft except ATS 6, for which Fairchild Industries was the prime contractor.

The information on the ATS program came from Ezell (1988, vol. II) and Rosenthal (1982).

11. Earth Resources Technology Satellite/Landsat

Earth Resources Technology Satellite (ERTS)/Landsat was NASA's first satellite program dedicated to remote sensing of Earth's environment and resources. Building on the experienced garnered during the OGO and Nimbus programs, the Landsat program nonetheless required the development of new technologies to address its mission objectives.

There had been enthusiasm expressed by government agencies like the U.S. Geological Survey and the Department of Agriculture for remote sensing of the Earth's resources and environment since the mid-1960s. By September 1966, the Department of Interior had publicly announced its intentions to plan an Earth Rescurces Observation Satellite that would use off-the-shelf technology.

NASA responded to the Interior announcement in April 1967, arguing that such a program would require significant development of sensor, data storage, and data transmission technologies. However, more significant than this exchange was that NASA accelerated its own Earth observation program, culminating in the launch of ERTS 1 in July 1972. By the time ERTS 2 was to be launched, NASA had changed the name of the satellites to Landsat. NASA then launched three additional Landsat satellites through the launch of Landsat-5 in March 1984.

By the time of the launch of Landsat-5, NASA had transferred operational responsibility for the Landsat satellites to the National Oceanic and Atmospheric

Administration (NOAA). The only exception was that NASA retained control of the Landsat Thematic Mapper instrument until 1985, when that too was transferred to NOAA.

Table 65. ERTS/Landsat Chronology

July 1964	NASA requested that the U.S. Geological Survey undertake studies of the possible applications of evolving instruments designed for remote sensing of the Earth and the Moon. The studies were to be jointly funded by NASA and the Interior Department.
February 1965	NASA initiated its Earth Resources Survey (ERS) Program to develop methods for the remote sensing of Earth resources from space.
March 1965	The Department of Agriculture began studying the applicability of remote sensing to solve agricultural problems.
September 1966	The Interior Department announced that a multi-agency Earth Resources Observation Satellites Program was being initiated to gather data about natural resources from Earth-orbiting instruments.
October 1966	The Interior Department submitted to NASA performance specifications for EROS, including spacecraft requirements.
February 1967	NASA began in-house Phase A feasibility studies of an ERTS. The studies concluded that ERTS was feasible using existing, although state-of-the-art equipment.
March 1967	NASA Headquarters authorized the Goddard Space Flight Center to study the feasibility of automated systems for ERTS.
July 1968	An interagency Earth Resources Survey Program Review Committee was established with participation from the USDA, the USN, the ESSA (NOAA), the USGS, and NASA.
January 1969	NASA signed the project approval document for Phase B/C ERTS.
April 1969	The interagency committee formally transmitted the ERTS design specifications to its members for approval.
May 1969	NASA issued request-for-proposals for definition and design of ERTS systems.
June 1969	NASA approved a contract with RCA for an ERTS RBV.
August 1969	NASA approved a contract with Hughes Aircraft for an ERTS MSS.
April 1970	NASA issued contracts to Hughes Aircraft for an MSS and to RCA for an RBV.
June 1970	Funds were approved for an ERTS tracking facility at Goddard.
July 1970	NASA announced its selection of GE as ERTS prime contractor.
September 1970	GE held the ERTS conceptual design review.
March 1971	NASA froze the ERTS A/B spacecraft design.
May 1971	NASA's contract with GE to be ERTS prime contractor was made definite.
July 1972	ERTS 1 was successfully launched.

In March 1983, President Reagan endorsed a recommendation to transfer the Landsat satellites to the private sector, along with existing weather satellites. Subsequent events led to a agreement between the EOSAT Corporation and the Department of Commerce under which EOSAT operates the Landsat ground system, builds and launches any additional Landsat satellites, and markets Landsat data on a world-wide basis. EOSAT

is a joint venture of GE and Hughes Aircraft, with the Computer Sciences Corporation as a major subcontractor.

Table 66. Landsat Programmed Funding History, 1969–78

Year	Landsat Spacecraft (millions of 1990 constant dollars)	Landsat Sensors (millions of 1990 constant dollars)
1969	5.57	3.24
1970	6.62	47.17
1971	78.10	76.05
1972	65.34	57.58
1973	19.12	62.74
1974	17.84	33.03[a]
1975	10.74	13.43
1976	19.35	12.41
1977	15.95	16.42
1978	30.95	64.98
Total	269.58	387.05

[a] Includes $2,975,000 for an MSS fifth band.

Table 67. ERTS/Landsat Spacecraft Characteristics

Spacecraft	Launch Date	Weight (kg)	Primary Instruments[a]
Lansat 1 (ERTS 1)	7/72	941	MSS, RBV
Landsat 2 (ERTS B)	1/75	953	MSS, RBV
Landsat 3 (ERTS C)	3/78	900	MSS, RBV
Landsat 4 (D)	7/82	—[b]	MSS, TM
Landsat 5 (D-prime)	3/84	—[b]	MSS, TM
Landsat 6		—[c]	ETM

[a] The listing of each spacecraft's instrument suite is for illustrative purposes only.

[b] Mass of 1941 kg at beginning of satellite life.

[c] Estimated of mass about 2750 kg at launch and about 2000 kg on-orbit at beginning of life.

The Landsat satellites have evolved throughout the program, although the principal focus of change has been the payload instruments. Landsats 1 and 2 were improved and enlarged Nimbus satellites, and carried the 3-band Return Beam Vidicon camera system (RBV). Landsats 1 and 2 also carried the Multispectral Scanner (MSS), which provided four-band coverage over a similar range. Landsat 3, also an improved Nimbus satellite, carried the MSS, with a fifth band of coverage for thermal-infrared emissions on the MSS, and an improved RBV.

Landsat 4 departed from its predecessors by being the first Landsat to carry the Thematic Mapper (TM), which covered additional spectral bands and had greater resolution

than the RBV. Landsat 5, which was originally the backup spacecraft for Landsat 4, also carried the TM. The latest Landsat spacecraft, Landsat 6, is to carry the Enhanced Thematic Mapper, which offers a 15 m panchromatic resolution capability and is capable of returning 900 scenes per day. The Sea Wide Field Sensor had been a candidate instrument for Landsat 6, but was deleted due to cost considerations. A thermal infrared detector and a 5 m, 3-band imager were also considered as Landsat-6 instruments, but were also omitted in the final payload.

The Goddard Space Flight Center had the management responsibility for the Landsat satellites and GE has been the prime contractor throughout the program.

The information on the ERTS/Landsat program is from several sources. For further information, see Ezell (1988, vol. III), Forecast International (1991a), Rosenthal (1982) and Wilson (1991).

12. Mariner

The Mariner program consisted of ten spacecraft designed for the purpose of orbital and flyby interplanetary exploration of Mars and Venus. The entire program lasted more than a decade, and went through what may be thought of as two or more phases. In the first phase, the first five Mariner spacecraft weighed in the 200-260 kg range and were designed strictly for "short" flyby missions to Mars and Venus. Mariners 6 and 7 also conducted these flyby missions. However, they embodied a transition to and a test of concepts for long-duration flight away from the sun. These long duration missions were achieved in the last two Mariner missions. Mariner 9 orbited Mars for nearly a year while Mariner 10 flew by Venus and then used the planet for an assist to three encounters with Mercury over a period of nearly a year. Mariner 9 weighed 997.9 kg and Mariner 10 weighed 528 kg.

The first Mariner spacecraft was launched in July 1962, while the last, Mariner 10, flew in November 1973. The Mariner program was managed by the NASA Headquarters Office of Lunar and Planetary Programs. However, the Jet Propulsion Lab (JPL) was the cognizant NASA center for the program. In addition, there were no commercial prime contractors for the task. Construction of the Mariner spacecraft was performed in-house in all cases, except for Mariner 10, which was built by the Boeing Company.

Table 68. Mariner Chronology

1958–59	Several feasibility studies for unmanned lunar and planetary missions resulted in conceptual designs for spacecraft using the planned Atlas-Centaur launch vehicle.
May 1960	NASA's planetary program was named Mariner.
July 1960	A study was begun at the JPL for Mariner A and Mariner B missions. Mariner B would attempt an instrumented landing. Both missions were approved by NASA Headquarters.
November 1960	JPL completed the preliminary design for Mariner A.
February 1961	Revised plans for Mariner A called for three missions to Venus between 1962 and 1965. Revised plans for Mariner B excluded a Venus landing.
August 1961	A study was begun at JPL for a Mariner-Venus fly by mission (also called Mariner R), which led to Mariner 1 and Mariner 2. However, later in the same month, Mariner A was canceled due to the projected unavailability of the Atlas-Centaur launch vehicle. Mariner-Venus 1962 was approved.
Early 1962	JPL began a design study for a Mariner-Mars 1964 craft for a flyby mission to Mars, which led to Mariner 3 and Mariner 4.
April 1962	Mariner B's Mars landing option was dropped and the Venus landing option was reconsidered.
July 1962	The Mariner 1 launch was unsuccessful.
November 1962	The Mariner-Mars 1964 project was tentatively approved.
March 1963	A project approval document for Mariner-Mars 1964 was signed. The Atlas-Agena launch vehicle was substituted for Atlas-Centaur, which was still behind schedule. The Mariner B mission was changed to a pre-Voyager checkout flight to Mars with a lander.
May 1963	Mariner-Mars 1966 flyby project was proposed to take the place of Mariner B.
December 1963	The Mariner-Mars 1966 mission was approved.
January 1964	Initial plans for an Advanced Mariner 1969 orbiter-lander to Mars were formulated.
July 1964	Mariner-Mars 1966 was effectively canceled, with official termination taking place in September. The Advanced Mariner 1969 was to replace it.
August 1964	A project approval document for Advanced Mariner 1969 was approved.
November 1964	Advanced Mariner 1969 was canceled due to budget considerations.
December 1965	A Mariner-Mars 1969 project, which led to Mariner 6 and 7, was approved when the Voyager Venus-Mars project was postponed. A Mariner-Venus 1967 project was also approved for the same reason. This project led to Mariner 5.
March 1966	A project approval document for Mariner-Mars 1969 was signed. The document approval had occurred in February.
April 1966	NASA issued Phase 1 request for proposals for Mariner-Mars 1969.
January-March 1967	JPL conducted a subsystem preliminary design review.
November 1967	Mariner-Mars 1971 was proposed, leading to Mariner 8 and Mariner 9, after the cancellation of Voyager. NASA officials conducted a launch vehicle system design review (of the Centaur upper stage?).
June 1968	Mariner Venus-Mercury 1973, which lead to Mariner 10, was proposed.
August 1968	A project approval document for Mariner-Mars 1971 was signed.
November 1968	JPL was authorized to begin work on Mariner-Mars 1971, specifically, the H and I spacecraft.
April 1971	NASA selected the Boeing Company to be prime contractor for the Mariner Venus Mercury spacecraft.
November 1973	Mariner 10 was launched successfully.

Table 69. Mariner Spacecraft Characteristics

Spacecraft	Launch Date	Weight (kg)	Dimensions (m) Base (shape)	Height (m)
Mariner 1 (Mariner R-1)	7/62	202.8	1.04 x .36 (hexagonal)	3.66
Mariner 2 (Mariner R-2)	8/62	202.8	1.04 × .36 (hexagonal)	3.66
Mariner 3 (Mariner C, Mariner-Mars 1964)	11/64	260.8	1.27 × .46 (octagonal)	2.89
Mariner 4 (Mariner D, Mariner-Mars 1964)	11/64	260.8	1.27 × .46 (octagonal)	2.89
Mariner 5 (Mariner E, Mariner-Venus 1967)	6/67	244.9	1.37 × .46 (octagonal)	2.89
Mariner 6 (Mariner-Mars 69)	2/69	381	1.37 (octagonal)	0.46
Mariner 7 (Mariner-Mars 69)	3/69	381	1.37 (octagonal)	0.46
Mariner H (Mariner 8, Mariner-Mars 71)	5/71	997.9	1.38 (octagonal)	2.44
Mariner 9 (Mariner-Mars 71)	5/71	997.9	1.38 (octagonal)	2.44
Mariner 10 (Mariner Venus Mercury 73)	11/73	528	1.39 (octagonal)	0.46

As suggested by the historical evolution of its missions, the Mariner design changed over time. However, all spacecraft consisted of a multifaceted base to which were attached the antenna, instruments, and two to four solar panels.

The Mariner 1, Mariner 3, and Mariner H, (i.e., Mariner 8), missions failed due to launch vehicle-related malfunctions. However, all other missions were considered to be successful.

The information on the Mariner came from a number of sources. For further information, see Ezell and Ezell (1984), Ezell (1988), and Rosenthal (1982).

13. High Energy Astronomy Observatory

The High Energy Astronomy Observatory (HEAO) program consisted of three earth-orbiting platforms that were equipped to collect high-quality, high resolution data on x-ray, gamma ray, and cosmic ray sources. The series of HEAO launches commenced in August 1977 with HEAO 1 and ended in September 1979 with HEAO 3.

The HEAO program was managed out of NASA Headquarters. The initial design studies were conducted at Marshall Space Flight Center, where project management resided throughout the program. The Goddard Space Flight Center served as the mission operations center. TRW was the prime contractor for the HEAO program.

Explorer 11 was NASA's first satellite to gather data on cosmic radiation. Its successors in the Small Astronomy Satellite Series (Explorers 42, 48, and 52) were launched during the 1970s to return data on x-ray, gamma-ray, and ultraviolet sources. However, discussions during the 1960s identified a requirement for a large satellite,

referred to as "Super Explorer," which would be dedicated to high-energy astronomical observations. The two HEAO satellites, as originally conceived, would weigh 9,700 kg and would carry experiments weighing 13,000 kg.

Table 70. HEAO Chronology

Spring 1969	Marshall Space Flight Center began a preliminary definition (Phase A) study for a HEAO.
February 1970	Marshall Space Flight Center issued an RFP for a phase preliminary design study.
April 1970	Marshall Space Flight Center held a preproposal briefing.
May 1970	Grumman and TRW were selected for phase B study contracts.
April 1971	Phase B studies completed.
July 1971	Marshall Space Flight Center issued an RFP for development, manufacture, and testing of two HEAO satellites.
October 1971	Announcement that Lockheed was building an Orbit Adjust Stage for use with the Titan III-D to place the HEAO into a circular orbit.
November 1971	NASA selects TRW to be prime contractor.
June 1972	NASA awards TRW a contract worth $83.65 million (TY) for two HEAO satellites with an expected launch on a Titan III-E in 1975.
January 1973	Budget cuts forced the suspension of HEAO for one year for the purpose of program restructuring and cost-cutting.
April 1974	Marshall Space Flight Center selected TRW to be prime contractor for the redefined HEAO program. Contract negotiations completed in August 1974.
September 1976	NASA reported to Congress that it had dropped two requirements for HEAO-C: retrievability by the Space Shuttle and compatibility with the Tracking and Data Relay Satellite System.
August 1977	HEAO 1 successfully launched.

Table 71. HEAO Programmed Funding History, 1972–78

Year	Funding (millions of 1990 constant dollars)
1972	45.17
1973	69.57
1974	14.43
1975	115.19
1976	145.85
1977	87.54[a]
1978	51.88
Total	529.63

[a] Includes $40,870,000 for development and $11,014,000 for mission operations.

Table 72. HEAO Satellite Characteristics

Spacecraft	Launch Date-End-of-Useful Life	Weight (kg)	Dimensions (m) Diameter/Length
HEAO (A)	3/79-9/79	2,575	2.35/6.10
HEAO 2 (Einstein Observatory)(B)	11/78-about 5/81	3,020	2.35/6.71
HEAO (C)	12/81-about 8/83	2,905	2.35/5.49

However, a later redesign necessitated by budget cuts replaced the two platforms with three platforms that would carry experiments weighing less than 3,000 kg. The three HEAO spacecraft were respectively dedicated to scanning x-ray experiments, to x-ray telescope observations, and to gamma-ray and cosmic ray scans.

The information on the HEAO program came from Ezell (1988, vol. III) and Rosenthal (1982).

14. Voyager

The Voyager program consisted of two spacecraft designed to fly by Jupiter and Saturn on a trajectory taking them out of the solar system. The project nominally ran between 1972 through the fall of 1977, when the two spacecraft were launched. Voyager 1 took the last of its images in 1990 from beyond Pluto. Voyager 2 reached its closest position to Neptune in 1989, and thereafter continued on a trajectory beyond the solar system.

The two Voyager spacecraft were identical, consisting of an 822 kg mission module, a 1211 kg propulsion module, and a 47 kg spacecraft adapter. Extending from the spacecraft's 10-sided central structure, which measured 0.47 m high and 1.78 m between faces, were a number of booms on which were mounted instruments and three radioisotope thermoelectric generators (RTG).

Voyager instruments included color television cameras, magnetometers, photopolarimeters, radio astronomy receivers, plasma wave instruments, plasma detectors, ultraviolet spectrometers, and other instruments. The instruments were mounted on a Science Scan Platform that could be rotated to point them toward their targets while maintaining the main 3.66m (diameter) high-gain antenna pointed toward the Earth.

The Voyager program was managed out of the Jet Propulsion Laboratory.

The information on the Voyager came from several sources. For further information, see Ezell and Ezell (1984), Ezell (1988, vol. III), NASA (1979), NASA (1977), Rosenthal (1982), and Wilson (1991).

15. Pioneer

The Pioneer consisted of two distinct space exploration programs, one lunar and one interplanetary. Four Pioneers were to fly to the moon in order to measure radiation, temperature, and micrometeoroid distribution. These spacecraft, originally designated the Able series of lunar probes, were incorporated into the fourth stage of the Thor Able launch vehicle that carried them. Able 1, which is not considered to be a Pioneer spacecraft, preceded Pioneer 1, the original Able 2 probe. Pioneer 2 also had an Able-series designation, Able 3. Able spacecraft 4, 5A, and 5B, which were to be launched between November 1959 and December 1960, were also not considered to be Pioneer spacecraft.

Five interplanetary Pioneers flew into solar orbit with the objective of measuring radiation, magnetic fields, cosmic dust and other solar phenomena. One Pioneer flew with a target of Jupiter, one with targets of Jupiter and Saturn, and two with Venus as the target. The first interplanetary Pioneer was launched on March 1969, and was followed by the rest of the series between December 1965 and August 1978.

The lunar Pioneer program was originally divided between the Air Force Ballistic Missile Division and Army Ballistic Missile Agency. However, NASA was given management responsibility for the lunar probe program in October 1958. Nonetheless, NASA Headquarters was the cognizant center for the lunar Pioneers, NASA delegated authority back to the military services for these spacecraft.

NASA did directly manage the interplanetary Pioneers, the first through the Goddard Space Flight Center, and the last eight through the Ames Research Center.

Space Technologies Laboratories (STL), eventually acquired by TRW, was the prime contractor to the Air Force for the first two lunar Pioneers. The Army contracted with the Jet Propulsion Laboratory for the third and fourth lunar Pioneers. STL manufactured Pioneer 5, the first interplanetary Pioneer, and manufactured all but the Venus Pioneer spacecraft under the TRW name after its acquisition by TRW.

The four lunar Pioneers consisted of two designs. Pioneers 1 and 2 had a shape of two truncated cones connected by a cylindrical midsection, whereas Pioneers 3 and 4 were conical in shape.

Table 73. Pioneer Chronology

March 1958	The Secretary of Defense announced that the Advanced Research Projects Agency would proceed with several programs for launching unmanned spacecraft. Three lunar probes were assigned to the Air Force and two were assigned to the Army.
1958	STL was awarded a contract for designing and manufacturing the Air Force's probe, and for modifying the second and third stages of the Thor Able launch vehicle.
August 1958	Launch of Able 1 lunar probe failed.
October 1958	NASA was given management responsibility for lunar probe program.
October 1958	Pioneer 1 launch failed when Thor Able stages failed to separate evenly.
March 1960	Pioneer 5 launch was successful.
May 1960	Ames Research Center began an informal study of solar probes.
September 1960	Ames Solar Probe Team was formed.
April 1962	TRW completed a feasibility study for Ames on designing a new interplanetary Pioneer.
November 1962	NASA approved a new series of Pioneer spacecraft. Project approval document for the Pioneer series was signed.
January 1963	NASA issued the RFP for the new Pioneer spacecraft.
August 1963	TRW was given a letter contract for the fabrication of five spacecraft ($1.5 million TY, maximum contract value).
April 1964	Final spacecraft design review.
July 1964	The definitive contract with TRW was signed.
December 1965	Pioneer 6 was launched successfully.
March 1972	The third generation Pioneer 10 was launched successfully.
May 1978	Pioneer Venus 1 probe was launched successfully.
August 1978	Pioneer Venus 2 probe was launched successfully.

The interplanetary Pioneers also had several distinct designs. Pioneer 5, launched in 1960, was spherical. However, the next four spacecraft shared a common design, and differed from their predecessor. These second generation interplanetary Pioneers, launched during the mid and late 1960s, were all cylindrical and had three booms and two antennas.

The third generation Pioneers, those launched toward the outer planets, were of three distinct types. Pioneers 10 and 11 were hexagonal spacecraft. The Venus Pioneers were different from their predecessors and designed according to their unique mission.

Only Pioneer 4 successfully entered a lunar trajectory, and it was only a partial success, inasmuch as it did not pass close enough to the moon for its photoelectric scanner to be effective. All interplanetary Pioneers were successful missions.

The information on the Pioneer came from several sources. For further information, see Corliss (1972), Ezell (1988), Rosenthal (1982), and TRW (1968).

Table 74. Pioneer Lunar Probes (Atlas-Able) Programmed Funding History, 1959-61

Year	Funding (millions of 1990 constant dollars)
1959	39.17[a]
1960	110.48[b]
1961	34.86[c]
Total	184.51

[a] Includes $25,729,160 for the Atlas-Able launch vehicle.

[b] Amount requested and funded for unspecified lunar probes.

[c] Includes funds for the launch vehicle.

Table 75. Pioneer Probes Programmed Funding History, 1960–68

Year	Funding (millions of 1990 constant dollars)
1960	22.87[a]
1961	2.70[b]
1962	—
1963	14.17
1964	70.54
1965	75.24
1966	60.10[c]
1967	31.13[c]
1968	25.68
Total	302.43

[a] For Pioneer 5, a precursor to the later Pioneer probe series.

[b] For a magnetometer probe, Explorer 10, the program's second interplanetary probe.

[c] Funded by the physics and astronomy budget in FY 1968–69 estimates.

Table 76. Pioneer/Helios Programmed Funding History, 1969–78

Year	Funding (millions of 1990 constant dollars)
1969	19.03
1970	85.5
1971	148.49
1972	51.45
1973	36.91
1974	20.84
1975	90.33
1976	151.97[a]
1977	102.97[b]
1978	44.99[c]
Total	752.48

[a] Includes $139,405,800 for Pioneer Venus, $9,605,700 for Pioneer 6-11, and $2,955,600 for Helios.

[b] Includes $95,187,200 for Pioneer Venus, $5,782,400 for Pioneer 6-11 extended mission, and $2,100,600 for Helios extended mission.

[c] Includes $36,927,700 for Pioneer Venus, $2,269,300 for Pioneer Venus extended mission, $4,344,678 for Pioneer 6-11 extended mission, and $1,444,100 for Helios extended mission.

Table 77. Pioneer Characteristics

Spacecraft	Launch Date	Weight (kg)	Shape/Dimensions (m)
Pioneer 1 (Able 2)	10/58	38.3	truncated cones joined by cylinder/.74 × .46
Pioneer 2 (Able 3)	11/58	39.2	truncated cones joined by cylinder/.74 × .46
Pioneer 3	12/58	5.9	.74 × .46
Pioneer 4	3/59	6.1	conical/.51 × .23
Pioneer 5	3/60	43	conical/.51 × .23
Pioneer 6	12/65	62.14	spherical/.66
Pioneer 7	8/66	62.75	cylindrical/.95 × .89
Pioneer 8	12/67	65.36	cylindrical/.95 × .89
Pioneer 9	11/68	65.36	cylindrical/.95 × .89
Pioneer 10	3/72	258	hexagonal/2.9 × 2.7 (greatest width)
Pioneer 11	4/73	270	hexagonal/2.9 × 2.7 (greatest width)
Pioneer Venus 1	5/78	582	cylindrical/1.2 × 2.5 (diameter)
Pioneer Venus 2	8/78		
Bus (total)		904	cylindrical/2.9 × 2.5 (diameter)
Large probe		316	conical/1.5 (diameter)
Small probe (each)		90	conical/.8 (diameter)

16. Magellan

The Magellan spacecraft was a radar-equipped orbiter whose mission to Venus was to map the surface of Venus and obtain data on its gravity field in order to investigate the planet's origin and evolution.

Launched by the Space Shuttle and the IUS in October 1989, Magellan followed a trajectory in which the spacecraft travels one-and-a-half times around the Sun before encountering Venus. Then the spacecraft's solid rocket motor is fired to put the spacecraft into orbit about Venus.

The concept of mapping Venus with a synthetic aperture radar (SAR) emerged during the late 1960s and early 1970s. The scientific objective for such a mission was established in a 1972 study at the Jet Propulsion Laboratory. The mission defined by this and subsequent studies was named the Venus Orbiting Imaging Radar (VOIR).

Table 78. Magellan Chronology

FY 1978	NASA initiated VOIR studies.
FY 1981	Full scale development planning for the VOIR mission takes place.
January 1982	VOIR program was canceled.
October 1983	VRM program was announced as a new project start.
December 1983	Magellan spacecraft contract was awarded to Martin Marietta. Magellan radar contract was awarded to Hughes Aircraft. The launch was scheduled for April 1988 using the Space Shuttle and Centaur upper stage and employing a direct ballistic trajectory.
FY 1985	Magellan project confirmation review, a comprehensive cost and status review, was held.
FY 1986	Residual hardware from the Galileo mission was no longer available for the Magellan spacecraft. The date is scheduled for October 1989.
October 1986	IUS selected to replace Centaur upper stage following Challenger accident.
FY 1987	The launch date is rescheduled from October 1989 to April 1989.
May 1989	Magellan was launched.
August 1990	Magellan entered orbit around Venus.
April 1991	Primary mapping mission was completed.

Science investigators for the VOIR mission were selected in 1979, but the VOIR was canceled in 1982 due to cost considerations. However, the VOIR mission reemerged in October 1983 under the name Venus Radar Mapper (VRM). NASA officially renamed VRM to be Magellan in 1986. In its evolution from VOIR, the Magellan mission was to be executed using elliptical orbits that are less demanding than the VOIR mission's circular orbits. The tradeoffs inherent in such a change are that the time required to map the planet's surface are more than doubled because mapping can be done during only a portion of each

orbit. However, the demands on telemetry are likewise reduced, and cut in half for the modified mission.

The Magellan spacecraft consisted of five main sections: a high-gain antenna, the forward equipment module, the spacecraft bus and solar array, the propulsion module, and the orbit insertion stage. The spacecraft's principal sensor was a synthetic aperture radar. Where possible, the spacecraft was fabricated using equipment derived from other spacecraft. It has been estimated that about 30% of the Magellan spacecraft's mass was specifically designed for the mission. This primarily involved the radar electronics and the spacecraft's solar panels.

The launch of the Magellan spacecraft was delayed by the Challenger accident in January 1987. It was also delayed by a subsequent decision not to carry the Centaur upper stage on the Space Shuttle. As result, the planned April 1988 launch date was stretched to April 1989. The IUS replaced the Centaur upper stage in the mission with no major changes to the spacecraft.

Table 79. Magellan Development Costs, 1984–87

Year	Costs (millions of 1990 constant dollars)
1984	34.40
1985	141.79
1986	270.78
1987	379.68
Total	826.65

Table 80. Magellan Characteristics

Mass (estimated)	
Injected	34785 kg
Dry	1046 kg
Dimensions	
Height	9.1 m
Maximum Diameter	6.3 m
High-Gain Antenna Diameter	3.7 m
Power	1.2 kw (maximum) from two solar panels

The Jet Propulsion Laboratory was the cognizant center for the Magellan program and the Martin Marietta Astronautics Group was the spacecraft prime contractor. Hughes Aircraft built the spacecraft's synthetic aperture radar.

A number of minor problems have occurred during the course of the Magellan mission, including the loss of data due to problems both on the spacecraft and at Deep Space Network stations. Overall, however, the Magellan program has been considered to have successfully attained its objectives.

As of 1987, the General Accounting Office had estimated that the cost of the project would be $513.5 million (TY), representing an increase of $219 million over the original estimate. This cost growth can be attributed in part to several causes. One was a decision to enlarge the scope of radar investigations and to improve the radar's resolving power. Another was problems at Hughes Aircraft with development of the radar. The third was the Challenger accident followed by the switch from the Centaur upper stage to the IUS.

The information on the Magellan came from several sources. For further information, see Forecast International (1991a), General Accounting Office (1988a), General Accounting Office GAO (1988b), Saunders et al. (1990), and Wilson (1991).

17. Galileo

The Galileo spacecraft was a combined orbiter-and-probe whose mission was to investigate Jupiter's atmosphere, characterize the physical and dynamic properties of Jupiter's satellites, and collect data on Jupiter's magnetosphere.

After years of schedule delay, the Galileo spacecraft was carried into Earth orbit by the Space Shuttle in October 1989. An IUS was used to leave earth orbit. Employing a Venus-Earth-Earth Gravity Assist (VEEGA), the orbiter will finally arrive at Jupiter in December 1995. The spacecraft will release its probe in July 1995.

Although the Jet Propulsion Laboratory was the cognizant center for the Galileo program, the Ames Research Center managed the fabrication of the Galileo probe. Hughes Aircraft built both the Galileo probe and the Galileo orbiter.

After launch from the Space Shuttle, NASA ground controllers discovered that the spacecraft's high gain antenna had failed to deploy. Successive attempts to free the antenna have failed. Ground controllers have been able to use alternate hardware to retrieve some data from the spacecraft's sensors at a reduced rate.

Table 81. Galileo Chronology

July 1977	Congress approved the program
FY 1978	Plans to follow up the Voyager missions with a Jupiter orbiter and probe mission started. The launch is scheduled for January 1982 using the Space Shuttle and the three-stage IUS using a direct ballistic trajectory.
	NASA advises the Jet Propulsion Laboratory (JPL) that the Space Shuttle's payload limit and the growth in the weight of the orbiter and IUS will require a new launch trajectory. JPL develops a Mars Gravity Assist trajectory to compensate for the payload weight limitations.
	Germany joins the program. Forecast International reports a total contribution by Germany of $40-50 million (TY).
June 1978	NASA chooses Hughes Aircraft to be the spacecraft prime contractor.
FY 1979	NASA advises JPL that the launch will be delayed due to delays in the Space Shuttle launch schedule. In response, JPL evaluates new launch alternatives.
FY 1980	NASA decides to split the orbiter and payload missions into separate Space Shuttle payloads. The launch is rescheduled from 1982 to earlv 1984.
	The orbiter, to be augmented by an auxiliary upper stage, was scheduled to be launched on a Mars Gravity Assist trajectory using NASA's three-stage IUS in February 1984. The probe was scheduled to be launched on a direct ballistic trajectory using NASA's three-stage IUS in Mar 1984.
	NASA decides to split the orbiter and payload missions into separate Space Shuttle payloads.
FY 1981	Cost increases in the three-stage IUS program result in NASA's decision to cancel its three-stage IUS and to plan the launch using the Centaur upper stage. This change allows reintegration of orbiter and probe missions using a direct ballistic trajectory strategy.
	The joint mission is postponed until April 1985 to accommodate Centaur development.
November 1980	NASA awarded a $40 million development contract (TY) to Hughes Aircraft for the Galileo orbiter.
FY 1982	NASA decides to cancel the Centaur project due to budgetary problems. NASA advises JPL that the mission is to be launched using the U.S. Air Force's two-stage IUS. The change results in a switch to a VEGA trajectory. The launch is rescheduled for August 1985.
	Congress then directed NASA to restart the Centaur project and to use the Centaur as the upper stage for the Galileo mission.
FY 1986	Following the Challenger accident, and for safety concerns, NASA replaces the Centaur upper stage with the U.S. Air Force IUS and lowers the Space Shuttle payload limit from 65,000 pounds to 51,100 pounds. This change precludes the use of the injection module anticipated for the Galileo mission and necessitates the VEGA trajectory. NASA postpones the launch from May 1986 to October 1989.
February 1987	The spacecraft is returned to JPL for storage.
December 1989	Galileo reassembly began.
February 1989	Galileo refurbishing began, to address issues of component aging.
October 1989	Galileo is launched as part of Space Shuttle Mission 34.
March 1991	Spacecraft places itself in safe mode following shutdown one of its computers. This reoccurred in May 1991.
April 1991	The high gain antenna failed to unfold following deployment commands from ground controllers.

Table 82. Galileo Spacecraft Characteristics

Mass	
Orbiter	2380 kg (excluding 118 kg payload and 1089 kg propellant)
Probe	338 kg (excluding 30 kg instruments)
Height	
Orbiter	4.5 m (in flight)
Probe	0.86 m (in flight)
Antenna	
Orbiter	4.8 m
Diameter	
Probe	1.25 m
Power	
Power	two radioisotope thermoelectric generators
Orbiter	0.57 kw
Requirements	
Probe	0.73 kw hours
Partial Instrumentation list	
Orbiter	Dust detector
	Plasma wave spectrometer
	Plasma detector
	Energetic Particles Detector (EPD)
	High Energy Ion Counter (HIC)
	Magnetometer
	Photopolarimeter radiometer
	Ultraviolet spectrometer
	Extreme Ultraviolet Spectrometer (EUVS)
	Near-Infrared Mapping Spectrometer (NIMS)
	Solid-state imagers
	Radio science celestial mechanics instruments
	Radio science propagation instrument
Probe	Atmospheric structure instrument
	Neutral mass spectrometer
	Helium abundance detector
	Nephelometer
	Net flux radiometer
	Lightning/energetic particles detector

Table 83. Galileo Cumulative Development Costs, 1978–86

Year	Funding (millions of 1990 constant dollars)
1978	35.40
1979	149.96
1980	143.77
1981	138.06
1982	157.30
1983	133.02
1984	106.87
1985	70.34
1986	73.74
Total	1,008.46

Note: In its Market Intelligence Report, Forecast International reports total spacecraft development costs of $540 million (TY). In addition, they report total program costs, including mission operations and data reduction/analysis, of $865 million (TY).

The information on the Galileo came from a number of sources. For further information, see Forecast International (1991a), General Accounting Office (1988c), and Wilson (1991).

18. Hubble Space Telescope

The Hubble Space Telescope (HST) was a spacebome astronomical observatory launched from the Space Shuttle in April 1990. The program was a joint effort by NASA and the European Space Agency.

At the time of initial funding (1978) the scheduled launch date for the HST was December 1983. However, managerial and technical problems reportedly resulted in a launch postponement to 1985. Technical problems resulted in another launch delay to October 1986, but the Challenger accident finally delayed the launch to June 1989, and then to December 1989. This last deferral was due to a preemptory requirement to retrieve the LDEF satellite using the Space Shuttle. The HST was finally carried into Earth orbit by the Space Shuttle in April 1990.

During the hiatus caused by the Challenger accident, a number of modifications were made to the HST as a result of observations made during verification testiong. Following a ground test in March 1987, all science instruments were removed for modification and to allow changes to the satellite's thermal protection system.

Thermal tests conducted during the post-Challenger hiatus revealed problems requiring modifications. Following these modifications, an exhaustive ground test satisfied NASA management that the HST's systems were ready for deployment.

With an expected operating life of at least fifteen years, the HST is the first major astronomical spacecraft designed for the exigencies of long-duration use. Early in the design phase, some of the major components identified as needing the most frequent maintenance, including most of the equipment in the support systems module equipment section, were designed as modular orbital replacement units (ORU). These units are self-contained boxes mounted in equipment bays, and removeable through doors or panels.

Standardization of many common elements, such as bolts and connectors, was intended to reduce the number of tools required for maintenance, and to simplify astronaut maintenance training. Finally, the exterior of the spacecraft is outfitted with handrails, foot-restraint sockets, and tether attachments, to facilitate astronaut extra-vehicular activities on the satellite.

Special provisions for HST maintenance are to be made in the Space Shuttle as well (Smith 1989, p. 416):

> The space support equipment (SSE) maintenance platform is a modified version of the Multi-mission Modular Spacecraft Flight Support Structure. It latches the HST at the three pins on its aft shroud, provides electric power and monitoring umbilical connections, and allows the entire HST to be rolled and tilted into positions convenient for astronaut work. The SSE maintenance platform is also used to attach the HST to the orbiter for the periodic reboost mission to correct for the decay of the HST orbit.

If necessary, the HST can be retrived and returned to earth in the payload bay of the Space Shuttle.

The Marshall Space Flight Center was reportedly responsible for overall management of the HST program, including building the spacecraft, on-orbit maintenance and any other maintenance required during its first year of operation. The Goddard Space Flight Center was responsible for scientific instruments (with the exception of the fine guidance sensors), mission operations, and data reduction, as well as any maintenance required after the first year.

Goddard was also responsible for the Space Telescope Science Institute, which is a private organization operated under a long-term contract with NASA by the Association of Universities for Research in Astronomy (AURA). The Institute implements NASA policies in the area of planning, management, and scheduling of scientific operations on the HST.

As a prime contractor, Lockheed Missile Systems was responsible for systems engineering and integration, in addition to SSM design and fabrication, HST assembly and verification, and launch and orbit verification. The Perkin-Elmer Corporation, now Hughes Danbury Optical, designed and built the OTA.

A number of problems that have been evident since its launch have degraded the performance of the HST. Spherical aberration in the primary mirror not detected during fabrication is to be corrected as part of the first servicing mission planned for the satellite. A robotic device named COSTAR (Corrective Optics Space Telescope Axial Replacement) will be used to install small mirrors to compensate for the flaws in the primary mirror. Ball Aerospace has been selected to build the COSTAR.

Other problems experienced by the HST have included solar array vibrations, which have been transmitted to the main satellite structure, and gyroscope failure. Software adjustments to correct for the vibrations have been attempted but were not globally successful at first. A redesigned solar panel array replacement has also been discussed as a candidate for a future servicing mission to the HST.

Table 84. Hubble Space Telescope (HST) Chronology

1971	Large space telescope studies began.
1973	Space telescope definition studies began.
1976	Space telescope definition studies completed.
October 1976	European Space Agency agreed to participation in the Space Telescope Program.
July 1977	NASA selected Lockheed to be the space telescope program prime contractor and Perkin Elmer to be the contractor for the OTA.
October 1977	NASA and the European Space Agency signed a memorandum of understanding for the space telescope project following Congressional approval.
	The primary mirror blank was cast by Corning Glass.
August 1980	Fine polishing of the primary mirror began.
December 1981	The primary mirror was aluminized.
July 1985	The OTA was delivered to Lockheed for integration.
1987	Ball Aerospace received a $46 million (TY) contract to develop the STIS instrument.
March 1987	Ground system test GST-3 was conducted, uncovering problems with HST instruments and subsystems.
June 1987	GST-4 was conducted successfully. The HST was subsequently stored until scheduled launch preparation.
March 1988	British Aerospace was awarded a contract to build the replacement solar panels.
April 1990	HST was launched aboard the Space Shuttle.

Table 85. HST Development Appropriations, FY 1978–88

Fiscal Year	Appropriations (millions of 1990 constant dollars)
1978	74.27
1979	149.21
1980	191.82
1981	184.44
1982	174.23
1983	246.01
1984	250.17
1985	241.02
1986	150.96
1987	110.69
1988	101.94
Total	1,874.76

Table 86. Hubble Space Telescope Characteristics

Mass	
Spacecraft (estimated)	11,600 kg
Mass	
Instrument (contractor)	
FOC (Matra Espace SA)	318 kg
GHRS (Ball Aerospace)	318 kg
HSP (University of Wisconsin)	273 kg
WF/PC (Jet Propulsion Laboratory)	270 kg
FOS (Martin Marietta)	309 kg

[a] Formerly Perkin-Elmer Corporation.

The information on the HST is from Forecast International (1991a), General Accounting Office (1988a), Smith (1989), and Wilson (1991).

19. Compton Gamma Ray Observatory

The Compton Gamma Ray Observatory (GRO) is a satellite whose function is to make gamma ray observations of the universe. Observations from its 450 km circular orbit are planned for fourteen day periods, during which the observatory is fixed at an altitude tailored to observing requirements. At the end of each observational period, the spacecraft is maneuvered to a new altitude using its own propulsion system. This propulsion system was also to be used to put the spacecraft into a higher orbit following its carriage to a 296 km orbit by the Space Shuttle. However, NASA

reportedly reconsidered this approach, opting instead to inject it directly into a 440-450 km orbit. The planned useful life of the spacecraft is two years.

The Goddard Space Flight Center is the cognizant NASA center for the GRO. TRW was the spacecraft prime contractor. The GRO acquisition program was characterized by a number of firsts as well as interesting practices. The GRO was the first spacecraft to be designed for on-orbit servicing and refueling. It was also said to be among the first spacecraft on which computer-aided design and manufacturing techniques were used from end to end. During fabrication, the GRO was built as an integrated structure, rather than being assembled out of separate platform and sensor components.

On the management side of the program, NASA and TRW had agreed to make the GRO spacecraft program a model for new and more productive ways of doing business. Based on this agreement, Goddard and TRW implemented a number of productivity measures and procedures. A computerized network and a video conference system was established to improve communications between the organizations.

As part of this effort, TRW implemented a computer-based performance measurement system adapted from the Peacekeeper program. Monthly cost data were entered into the computer that could then automatically display program status at five levels of work breakdown structure. Other displays were available for manpower plots, performance factors, and cost, budget, and schedule status. A computer-based critical path schedule network also provided cost and schedule data.

TRW also implemented an individual reward system to recognize cost-savings suggestions from its employees. Cost savings in excess of $4.5 million have been reported for this program.

Finally, TRW constructed a full-size mockup to provide a tool for design verification, instrument fit checks, and personnel training. In particular, the mockup was also immersed in a pool at a Weightless Environment Test Facility to allow astronauts to practice on-orbit tasks with the satellite. The mockup thus allowed feedback from the astronauts to be considered with respect to spacecraft maintenance.

Several sources report that the total cost of the program just before launch, as reported by NASA, was $557 million. According to Bulloch (1991, p. 23):

> The prime contractor's share of this (presumably including the relatively small payments to subcontractors) was $268 million at completion, according to TRW's Stan Reib. It had risen by just under 62% in constant dollars from a baseline price of $177 million established in February 1983, just after TRW and NASA had initiated a product improvement program which actually saved money.
>
> Of the $109 million increase, about half can be attributed to "approved STS scheduling changes", a euphemism for the post-Challenger Shuttle stand-down which prevented GRO from being launched in 1988. Reib says that practically all of this additional funding ($50 million) was required "just to maintain the cadre of people" involved in the program. Staffing at TRW assigned to GRO peaked at 225 in 1988.
>
> Another $19 million (17.4% of the increase) was needed to cover "technical changes approved by NASA" for which TRW is not held responsible. Most of these involved instrument interfaces: while "instrument design started considerably ahead of the time we got into detailed design" of the satellite, Reib tells Interavia Space Markets, [this task] "was finished late ... we needed to make certain changes to the spacecraft to accommodate the instruments." These included additional structural stiffening.
>
> TRW acknowledges that $34 million (31%) of the overrun is "due to technical complexity", chiefly involving the structure. Rieb says the "total parts count grew dramatically" from 700 parts initially to 1100. Also, TRW 'had not fully appreciated the very large size of the observatory in terms of handling requirements. There were also difficulties with the cable harness.
>
> NASA has awarded TRW an average of 95% of its incentive fees over the eight years since the contract was signed. The contractor received quality and productivity awards in 1988-90. However, given the projected overrun, the fee will at best offset TRW's initial corporate investment.

The information on the GRO program came from a number of sources. For further information, see Bulloch (1991), Forecast International (1991a), and Wilson (1991).

Table 87. Compton Gamma Ray Observatory Chronology

February 1980	GRO concept studies commenced. Launch originally scheduled for 1984.
April 1981	TRW received the GRO engineering contract.
May 1984	Preliminary design review.
June 1985	Critical design review.
January 1989	GRO launch from the Space Shuttle was rescheduled for April 1990.
August 1989	Thermal vacuum testing complete.
January 1990	Launch was rescheduled to November 1990 to avoid work scheduling problems with the Ulysses spacecraft. Space Shuttle hydrogen leak problems eventually pushed the launch date into 1991.
February 1990	Spacecraft delivery to Kennedy Space Center
April 1991	GRO was launched.

Table 88. Compton Gamma Ray Observatory Spacecraft Characteristics

Mass	15,876 kg (at liftoff)
Dimensions	4.6 m (height) × 7.6 m (length) × 3.8 m (diameter) (stowed)
Power source	Two solar arrays (36.79 m^2) providing 4.3 kw at the end of the mission life.
Propulsion	Four 100 pound thrusters on the Orbit Adjust Thruster Module (OATM) and two 5-pound thrusters on each of four Dual Thruster Modules (DTM)
Instruments	
Imaging Compton Telescope (COMPTEL)	about 22284 kg
Oriented Scintillation Spectrometer Experiment (OSSE)	about 1805 kg
Burst and Transient Source Experiment (BATSE)	about 95 kg
Energetic Gamma Ray Experiment Telescope (EGRET)	about 1813 kg

20. Upper Atmosphere Research Satellite

The Upper Atmosphere Research Satellite (UARS) was built with the objective of investigating the structure and dynamics of the earth's upper atmosphere. Particular interest was in the process of stratospheric ozone depletion, although observations were also to be made of solar radiation and solar-atmospheric interactions. Data collection was reportedly being coordinated with that collected by the NOAA satellites' SBUV instrument.

The UARS spacecraft has been reported to weigh about 7,711 kg in the Space Shuttle cargo bay, but 6800 kg on orbit BOL. (Other reports give UARS weight to be 6480 kg, e.g., *Space News*, September 9, 1991, p.24). This includes an instrument payload weight of 2,268 kg.

Table 89. UARS Chronology

September 1978	UARS program opportunity was announced.
September 1980	UARS instrument definition phase began.
March 1984	UARS system design request for proposals was issued.
March 1985	UARS design development began. The UARS observatory contract was awarded to GE (contract value of $145.8 million, TY).
August 1985	NASA awarded Fairchild Space a $16.3 million (TY) contract to integrate and test a mulitimission, modular UARS spacecraft.
May 1986	NASA's Earth Systems Sciences Committee listed UARS as part of a plan to study earth systems properties and processes.
1986	Observatory preliminary design review.
1987	Observatory critical design review.
October 1991	UARS was launched.

Table 90. Principal UARS Instruments

Atmospheric chemistry and temperature:
Microwave Limb Sounder (MLS)
Cryogenic Limb Array Etalon Spectrometer (CLAES)
Improved Stratospheric and Mesospheric Sounder (ISAMS)
Halogen Occultation Experiment (HALOE)
Atmospheric winds mapping:
Wind Imaging Interferometer (WIND2)
High Resolution Doppler Imager (HRDI)
Solar-atmospheric interactions:
Solar Ultraviolet Spectral Irradiance Monitor (SUSIM)
Solar-Stellar Irradiance Comparison Experiment (SOLSTICE)
Magnetic field/charged particle observations:
Particle Environment Monitor (PEM)
Solar radiation observations:
Active Cavity Radiometer Irradiance Monitor (ACRIM2)

The Goddard Spaceflight Center was the NASA cognizant center for the UARS program. GE was responsible for UARS observatory design, and the design, fabrication, and testing of an instrument module compatible with Fairchild Space Company's Multi-mission Modular Spacecraft (MMS) design. Fairchild Space was responsible for integrating and testing the MMS.

The information on the UARS program came from Wilson (1991) and Forecast International (1991b).

V. INSTRUMENTS

During this study, we examined four instrument cost models: the Scientific Instrument Cost Model (Planning Research Corporation 1990b) and the Multi-Variable Instrument Cost Model (MICM) from Goddard Space Flight Center (Dixon and Villone 1990 and Fryer and Villone 1991), the instrument portion of the NASA Cost Model (NASCOM) from the Marshall Space Flight Center (Planning Research Corporation 1990a), and an instrument cost model (Borden, Schwartz, and Smith 1986) developed by the Jet Propulsion Laboratory (JPL). The Scientific Instrument Cost Model (SICM) and NASCOM were prepared for NASA by the Planning Research Corporation (PRC). All four models use the PRC instrument data base—JPL uses the data base as of 1985, while SICM, MICM, and NASCOM are based on data that have been updated to 1990.

The four models can be distinguished both by their segregation within the data base and by the form and construction of their CERs. In a broad sense, the models can be separated into two groups: first, the weight-based models, NASCOM and SICM, and second, those including other independent variables, JPL and MICM. The following presentation summarizes the essential features of the models and is intended to provide the analyst with an understanding of what presently exists in the field. The references provide more detailed information on the models and data sets. Due to classification, only the functional forms of the CERs are presented here.

An examination of the models reveals a universal shortcoming: all four models estimate costs at the complete instrument level. The only cost breakdown is into recurring and non-recurring costs, referred to as "Flight Unit" and "DDT&E" (Design, Development, Test and Evaluation). As a result of discussions with members of the instrument production community and technical experts within IDA, we believe the next step in improving instrument cost estimating is to collect instrument cost and technical information at the sub-system rather than the system level. With a more homogeneous sub-system data base, we would expect some sub-system technical variables in addition to weight to consistently enter the equations.

A. COST MODELS

The SICM segregates the data into the eighteen instrument categories listed in Table 91.[3] For each instrument category, two CERs are developed: one for Design, Development, Test and Evaluation (DDT&E) cost, and another for Flight Cost, resulting in thirty-six CERs. Both costs apply to the complete instrument and no further breakdown of cost is provided. Often, some of the data points are excluded from the CER with specific reasons given in each case. All CERs in the SICM are established by regression analysis and, with the exception of the CERs for lasers which are based on input power, are a multiplicative form with weight as the only independent variable:

$$\text{Cost} = C_1 * (\text{Weight})^{C_2}.$$

Table 91. SICM Instrument Categories

Category Number	Instrument Category
1	Photometer
2	Spectrometer
3	Spectroheliograph
4	Telescope
5	Interferometer
6	Radiometer
7	High Resolution Mapper
8	Magnetometer
9	Electric Field
10	Charge and X-Ray Detection
11	Mass Measurement
12	Plasma Probe
13	Active Microwave
14	Passive Microwave
15	Laser
16	Pyrheliometer
17	Film Camera
18	Television Camera

Instrument costs are only a part of NASCOM, which also covers manned and unmanned spacecraft, and launch vehicles. As with SICM, the instrument portion of NASCOM also segregates the data by instrument type, but then further categorizes each type into instruments for earth orbital missions versus those for planetary missions. Table 92 displays is a comparison of the instrument categories used in SICM and NASCOM. Recall that both use the same PRC data base. The blanks result from NASCOM

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[3] The nineteenth instrument category, Miscellaneous, is ignored here since no CERs were developed for it.

not examining a particular instrument category or, in some cases, a category not containing any instruments for planetary missions.

Table 92. SICM and NASCOM Coverage of Instrument Categories

Category Number	SICM Instrument Category	NASCOM Earth Orbiting Instruments	NASCOM Planetary Instruments
1	Photometer	X	X
2	Spectrometer	X	X
3	Spectroheliograph	X	
4	Telescope	X	
5	Interferometer	X	X
6	Radiometer	X	X
7	High Resolution Mapper		
8	Magnetometer	X	X
9	Electric Field	X	X
10	Charge and X-Ray Detection	X	X
11	Mass Measurement	X	X
12	Plasma Probe	X	X
13	Active Microwave	X	
14	Passive Microwave	X	
15	Laser	X	X
16	Pyrheliometer		
17	Film Camera		
18	Television Camera		

For each instrument category, NASCOM has CERs for DDT&E and Flight Unit Cost of the same form as SICM: Cost = C_1*(Weight)^{C_2}. This gives NASCOM forty-eight CERs, twenty-eight for earth orbiting instruments and twenty for planetary instruments. However, in contrast to SICM where the values of C_1 and C_2 are determined through regression, NASCOM uses an "average first pound cost" (C_1) for each instrument category and default values for the slope (C_2). The default slope values, 0.5 for DDT&E and 0.7 for Flight Cost, are based on engineering judgement and the average slope from other cost models.

The JPL study used the 1985 PRC instrument data base. All the instruments in the JPL study are included in the 1990 PRC data base used in SICM and NASCOM. In establishing the data set for the study, JPL took two major steps. First, they removed all data points from before 1975. Second, JPL added several subjective variables such as the general complexity of the instrument (on a scale of 1 to 3) and the amount of inheritance an instrument received from previous development projects (on a scale of 1 to 3).

Whereas, SICM and NASCOM have CERs for each instrument category, the JPL study developed three CERs covering all 90 instruments in its data base: one for DDT&E, another for Flight Unit Cost, and a third for Total Cost, the sum of the first two. JPL uses

the the same instrument categories as the SICM, but employs dummy variables in the CERs to distinguish between categories. By this method, only the categories whose dummy variables are statistically significant are distinguished by the CER.

In Table 93 there is a comparison of the instrument categories used by SICM and JPL. In its CERs, the JPL model distinguishes only photometers, spectroheliographs, and high resolution mappers from the remaining instrument categories.

Table 93. SICM and JPL Instrument Categories

Category Number	SICM Instrument Category	JPL Category Coverage	Category Dummy Variable Retained in CER
1	Photometer	X	X
2	Spectrometer	X	
3	Spectroheliograph	X	X
4	Telescope	X	
5	Interferometer	X	
6	Radiometer	X	
7	High Resolution Mapper	X	X
8	Magnetometer	X	
9	Electric Field	X	
10	Charge and X-Ray Detection	X	
11	Mass Measurement	X	
12	Plasma Probe	X	
13	Active Microwave	X	
14	Passive Microwave	X	
15	Laser	X	
16	Pyrheliometer		
17	Film Camera[a]		
18	Television Camera[a]		

[a] Film Camera and Television Camera were not separate instrument categories in the 1985 PRC data base used by JPL.

The three CERs developed by JPL have the following form:

1) DDT&E Cost = C_1*(Weight)$^{(C_2 + C_3*PHO + C_4*SPH + C_5*HRM)}$ * EXP (C_6*COMPLX + C_7*CMPTS + C_8*CLASS + C_9*SCHED),

2) Flight Unit Cost = C_1*(Weight)$^{(C_2 + C_3*PHO)}$ * EXP (C_4*CMPTS + C_5*CLASS + C_6*SCHED + C_7*SPH + C_8*HRM),

3) Total Cost = C_1*(Weight)$^{(C_2 + C_3*PHO + C_4*SPH + C_5*HRM)}$ * EXP (C_6*COMPLX + C_7*CMPTS + C_8*CLASS + C_9*SCHED),

where

PHO = Dummy variable for photometers

SPH = Dummy variable for spectroheliographs

HRM = Dummy variable for high resolution mappers

COMPLX = A value for the complexity of an instrument obtained by adding the general complexity of the instrument's category (on a scale of 1 to 3) to the complexity of the instrument with respect to the other instruments in the same category (on a scale of 1 to 3).

CMPTS = The number of components in the instrument inferred from component breakdowns by instrument category.

CLASS = Ratings of instrument reliability derived from the instrument class system initiated in 1977. In order to reflect the non-linear increase in reliability across the classes, JPL assigned this variable values of 2, 5, 8, or 10, with higher values indicating higher reliability. The class rating system is based on quality control methods used and the emphasis of reliability in the design, and not directly on empirical data such as mean time to failure.

SCHED = The number of years between the start date and the delivery of the instrument (delivery year – start year).

As an alternative to the weight-based SICM, Goddard developed the MICM. As an estimator of cost, weight based equations conflict with the trend in the instrument industry of miniaturization. Modern instrument designers employ sophisticated and often expensive technolcgies to reduce the weight and volume of instruments to meet spacecraft payload constraints. An equation limited to weight underestimates the cost of such instruments.

While SICM has CERs both for each class of instrument and for recurring and non-recurring costs, MICM has only a single CER for total instrument cost covering the entire data set. If recurring and non-recurring must be separated, the recommended approach is to use the average proportion between the two costs from the corresponding instrument category of the SICM cost data base.

The single MICM equation for total instrument cost is of the form:

$$\text{Total Unit Cost} = C_1*(WT)^{C_2}*(PWR)^{C_3}*(YR)^{C_4}*(DRT)^{C_5}*(FAM)^{C_6}*(CLS)^{C_7},$$

where

WT = instrument weight, lbs.

PWR = peak input power, watts

YR = number of years after 1960 that launch occurs

DRT = peak data rate, kilobits per second

FAM = complexity scaling assigned to each of the instrument families in the MICM

CLS = values for five mission classes developed to represent both design life and reliability

Using the SICM data base, we searched for possible CERs beyond the standard weight based equations but still segregating the data by instrument type. No other technical characteristics were significant.

B. THE SICM DATA BASE

The data summarized in this section are from the SICM (Planning Research Corporation 1990b). The data consist of 366 instruments, primarily earth-orbiting satellite instruments but including some Space Shuttle payloads and interplanetary instruments. The instruments in the data base are listed in Table 94 with their associated categories, platforms, and launch dates.

The two volume documentation of the SICM contains a detailed presentation of the data base including component breakdowns and descriptions for a majority of the data. No attempt is made here to duplicate the content of the SICM documentation. What follows is a summary of the instrument data by SICM category. The nineteenth category, miscellaneous, is not included in the summary. The column labeled "N" is the number of instruments for which data existed for the corresponding variable. Therefore, the largest value of "N" is the number of instruments contained in that category and is almost always the value of "N" for the cost variables.

1. Photometers

Photometers measure the intensity of electromagnetic energy from the visible light to the extreme ultraviolet regions. Other instrument types in this category include general light monitors, polarimeters, photopolarimeters, spectrophotometers, and chronographs. Polarimeters and photopolarimeters determine rotations in the plane of polarization of polarized light under various conditions. Spectrophotometers combine a spectrometer, an instrument for examining spectra, with a photometer to measure the intensity of light as a function of wavelength. A chronograph allows observations of the corona and prominences of the sun by using occulting disks to form an artificial eclipse of the sun. The SICM data base contains 25 instruments in this category.

Table 94. Summary Statistics of Instruments Data

Instrument	Category	Platform	Launch Date
Bennett Ion Mass Spectrometer	Mass Measurement	AE-3	12/16/73
Magnetic Ion Mass Spectrometer	Mass Measurement	AE-3	12/16/73
Neutral Atmosphere Composition Experiment	Mass Measurement	AE-3	12/16/73
Neutral Atmospheric Temperature Experiment	Mass Measurement	AE-3	12/16/73
Open Source Neutral Mass Spectrometer	Mass Measurement	AE-3	12/16/73
Atmospheric Density Accelerometer	Miscellaneous	AE-3	12/16/73
Extreme Solar UV Monitor (ESUM)	Photometer	AE-3	12/16/73
Solar Extreme UV Spectophotometer	Photometer	AE-3	12/16/73
Visible Airglow Experiment (VAE)	Photometer	AE-3	12/16/73
Cylindrical Electrostatic Probe (CEP)	Plasma Probe	AE-3	12/16/73
Low Energy Electron Experiment	Plasma Probe	AE-3	12/16/73
Photoelectron Spectrometer	Plasma Probe	AE-3	12/16/73
Retarding Potential Analyzer	Plasma Probe	AE-3	12/16/73
UV Nitric Oxide Spectrometer	Spectrometer	AE-3	12/16/73
Neutral Atmosphere Temperature Experiment	Mass Measurement	AEROS-B	7/16/74
Medium Energy Particle Analyzer	Charge and X-Ray Detection	AMPTE/CCE	8/16/84
Plasma Wave Experiment	Electric Field	AMPTE/CCE	8/16/84
Hot Plasma Composition Experiment	Mass Measurement	AMPTE/CCE	8/16/84
Charge-Energy-Mass Spectrometer	Plasma Probe	AMPTE/CCE	8/16/84
UV Experiment	Spectrometer	ANS-1	8/30/74
Lunar Topographic Camera	Film Camera	Apollo-13	4/11/70
24-Inch Panoramic Film Camera	Film Camera	Apollo-15	7/26/71
3-Inch Mapping Camera	Film Camera	Apollo-15	7/26/71
Particles and Field Subsatellite Magnetometer	Magnetometer	Apollo-15	7/26/71
Laser Altimeter	Laser	Apollo-15 and 17	12/7/72
Extreme Ultraviolet Astronomy	Photometer	ASTP	7/15/75
Helium Glow Detector	Photometer	ASTP	7/15/75
Wide Field Camera	Miscellaneous	ASTRO-1	4/26/90
Hopkins Ultraviolet Telescope	Telescope	ASTRO-1	4/26/90
Ultraviolet Imaging Telescope	Telescope	ASTRO-1	4/26/90
Wisconsin Ultraviolet Photo-Polarimeter Experiment	Telescope	ASTRO-1	4/26/90
Spin-Scan Cloud Camera	Telescope	ATS-1	12/7/66
Advanced Vidicon Camera System	TV Camera	ATS-2	4/6/67
Multi-Color Spin-Scan Cloud Camera	Telescope	ATS-3	11/5/67
Image Dissector Camera System	TV Camera	ATS-3	11/5/67

Table 94. Summary Statistics of Instruments Data (Continued)

Instrument	Category	Platform	Launch Date
Multi-Color Spin-Scan Cloud Cover Camera	TV Camera	ATS-3	11/5/67
Image Orthicon Camera	TV Camera	ATS-4	8/10/68
Omnidirectional Particle Detector	Charge and X-Ray Detection	ATS-5	8/12/69
Trapped Radiation Detector	Charge and X-Ray Detection	ATS-5	8/12/69
Auroral Particles	Plasma Probe	ATS-5	8/12/69
Particle Acceleration Measurement	Charge and X-Ray Detection	ATS-6	5/30/74
Magnetometer	Magnetometer	ATS-6	5/30/74
Rf Interferometer Subsystem	Passive Microwave	ATS-6	5/30/74
Auroral Particles	Plasma Probe	ATS-6	5/30/74
Low Energy Proton-Electron	Plasma Probe	ATS-6	5/30/74
Very High Resolution Radiometer	Radiometer	ATS-6	5/30/74
Far Infrared Absolute Spectrometer (FIRAS)	Interferometer	COBE	11/18/89
Dewar	Miscellaneous	COBE	11/18/89
Differential Microwave Radiometer (DMR)	Passive Microwave	COBE	11/18/89
Diffuse Infrared Background Experiment (DIRBE)	Radiometer	COBE	11/18/89
Energy Spectrometer	Charge and X-Ray Detection	COS-B	8/8/75
Plasma Wave Instrument	Electric Field	DE-1	8/3/81
Plasma Wave Instrument	Magnetometer	DE-1	8/3/81
Spin-Scan Auroral Imager (SAI)	Photometer	DE-1	8/3/81
High Altitude Plasma Instrument	Plasma Probe	DE-1	8/3/81
Fabry-Perot Interferometer (FPI)	Interferometer	DE-2	8/3/81
Neutral Atmosphere Composition Spectrometer	Mass Measurement	DE-2	8/3/81
Wind And Temperature Spectrometer	Mass Measurement	DE-2	8/3/81
Low Altitute Plasma Instrument	Plasma Probe	DE-2	8/3/81
Earth Radiation Budget Experiment Non-Scanner	Pyrheliometer	ERBS	10/5/84
Earth Radiation Budget Experiment Scanner	Radiometer	ERBS	10/5/84
Stratospheric Aerosol and Gas Experiment II	Spectrometer	ERBS	10/5/84
Advanced Vidicon Camera System	TV Camera	ESSA-3	10/2/66
Plasma Wave Spectrometer	Electric Field	Galileo Orbiter	10/18/89
Magnetometer	Magnetometer	Galileo Orbiter	10/18/89
Plasma Wave Spectrometer	Magnetometer	Galileo Orbiter	10/18/89
Energetic Particles Detector	Mass Measurement	Galileo Orbiter	10/18/89
Solid State Imaging	Miscellaneous	Galileo Orbiter	10/18/89
Photopolarimeter/Radiometer (PPR)	Photometer	Galileo Orbiter	10/18/89
Plasma Detector	Plasma Probe	Galileo Orbiter	10/18/89

Table 94. Summary Statistics of Instruments Data (Continued)

Instrument	Category	Platform	Launch Date
Near Infrared Mapping Spectrometer (NIMS)	Spectrometer	Galileo Orbiter	10/18/89
Ultraviolet Spectrometer (UVS)	Spectrometer	Galileo Orbiter	10/18/89
Neutral Mass Spectrometer	Mass Measurement	Galileo Probe	10/18/89
Atmosphere Structure Instrument	Miscellaneous	Galileo Probe	10/18/89
Nephelometer	Miscellaneous	Galileo Probe	10/18/89
Lightning And Radio Emissions	Photometer	Galileo Probe	10/18/89
Net Flux Radiometer	Radiometer	Galileo Probe	10/18/89
Vissr Atmospheric Sounder (VAS)	Radiometer	GEOS-4	9/9/80
Radar Altimeter	Active Microwave	GEOS-C	4/9/75
Burst And Transient Source Experiment (BATSE)	Charge and X-Ray Detection	GRO	6/4/90
Energetic Gamma-Ray Experiment Telescope (EGRET)	Charge and X-Ray Detection	GRO	6/4/90
Imaging Compton Telescope (COMPTEL)	Charge and X-Ray Detection	GRO	6/4/90
Oriented Scintillation Spectrometer Experiment (OSSE)	Charge and X-Ray Detection	GRO	6/4/90
Elf/Vlf Receivers	Electric Field	Hawkeye	6/3/74
Fluxgate Magnetometer	Magnetometer	Hawkeye	6/3/74
Heat Capacity Mapping Radiometer	Radiometer	HCMM	4/26/78
Cosmic X-Ray Experiment	Charge and X-Ray Detection	HEAO-1	8/12/77
Hard X-Ray and Low-Energy Gamma-Ray Experiment	Charge and X-Ray Detection	HEAO-1	8/12/77
Large Area X-Ray Survey Experiment	Charge and X-Ray Detection	HEAO-1	8/12/77
X-Ray Scanning Modulation Collimator	Charge and X-Ray Detection	HEAO-1	8/12/77
Aspect Sensor/South Atlantic Anomaly Detector	Charge and X-Ray Detection	HEAO-2	11/13/78
Focal Plane Crystal Spectrometer	Charge and X-Ray Detection	HEAO-2	11/13/78
High Resolution Imager	Charge and X-Ray Detection	HEAO-2	11/13/78
Imaging Proportional Counter	Charge and X-Ray Detection	HEAO-2	11/13/78
Monitor Proportional Counter	Charge and X-Ray Detection	HEAO-2	11/13/78
Objective Grating/Broad Band Filter Spectrometer	Charge and X-Ray Detection	HEAO-2	11/13/78
Pre-Collimator/Sun Shade	Charge and X-Ray Detection	HEAO-2	11/13/78
Solid State Spectrometer	Charge and X-Ray Detection	HEAO-2	11/13/78
Aspect Sensor/South Atlantic Anomaly Detector	Photometer	HEAO-2	11/13/78
Objective Grating/Broad Band Filter Spectrometer	Spectrometer	HEAO-2	11/13/78
Focal Plane Assembly	Telescope	HEAO-2	11/13/78
High Resolution Mirror Assembly	Telescope	HEAO-2	11/13/78
Optical Bench	Telescope	HEAO-2	11/13/78
Pre-Collimator/Sun Shade	Telescope	HEAO-2	11/13/78
Telescope Assembly	Telescope	HEAO-2	11/13/78

Table 94. Summary Statistics of Instruments Data (Continued)

Instrument	Category	Platform	Launch Date
Gamma Ray Spectrometer	Charge and X-Ray Detection	HEAO-3	9/20/79
Heavy Nuclei Experiment	Charge and X-Ray Detection	HEAO-3	9/20/79
Isotopic Composition Of Cosmic Rays	Charge and X-Ray Detection	HEAO-3	9/20/79
Cosmic Ray Range Versus Energy Loss	Charge and X-Ray Detection	IMP-1	11/27/63
Retarding Potential Analyzer	Plasma Probe	IMP-1	
Cosmic Ray Experiment	Charge and X-Ray Detection	IMP-6	3/13/71
Fluxgate Magnetometer	Magnetometer	IMP-6	3/13/71
Charged Particle Measurement Experiment	Charge and X-Ray Detection	IMP-7	9/23/72
Electron Isotope Spectrometer	Charge and X-Ray Detection	IMP-7	9/23/72
Ion And Electron Experiment	Charge and X-Ray Detection	IMP-7	9/23/72
Low Energy Particles (LEPEDEA)	Plasma Probe	IMP-7	9/23/72
Ac Electric And Magnetic Fields	Electric Field	IMP-8	10/26/73
Dewar	Miscellaneous	IRAS	1/25/83
Infrared Ritchey-Chretien Telescope	Telescope	IRAS	1/25/83
Electrons And Protons	Charge and X-Ray Detection	ISEE-1	8/12/78
Dc Electric Fields	Electric Field	ISEE-1	10/22/77
Plasma Wave	Electric Field	ISEE-1	10/22/77
Plasma Wave	Magnetometer	ISEE-1	10/22/77
Triaxial Fluxgate Magnetometer	Magnetometer	ISEE-1	10/22/77
Hot Plasma Composition	Mass Measurement	ISEE-1	10/22/77
Hot Plasma (LEPEDEA)	Plasma Probe	ISEE-1	10/22/77
Hot Plasma Composition	Plasma Probe	ISEE-1	10/22/77
High Energy Cosmic Rays	Charge and X-Ray Detection	ISEE-3	8/12/78
Solar X-Ray Experiment	Charge and X-Ray Detection	ISEE-3	8/12/78
Helium Vector Magnetometer	Magnetometer	ISEE-3	8/12/78
Solar Electron Experiment	Plasma Probe	ISEE-3	8/12/78
Polar Ionospheric X-Ray Imaging Experiment	Charge and X-Ray Detection	ISTP (Polar)	6/93
Electric Fields	Electric Field	ISTP (Polar)	6/93
Plasma Waves	Electric Field	ISTP (Polar)	6/93
Magnetic Fields	Magnetometer	ISTP (Polar)	6/93
Plasma Waves	Magnetometer	ISTP (Polar)	6/93
Torodial Ion Mass Spectrograph	Mass Measurement	ISTP (Polar)	6/93
Optical Auroral Imager	Photometer	ISTP (Polar)	6/93
Charge and Magnetospheric Ion Composition Experiment	Plasma Probe	ISTP (Polar)	6/93
Comprehensive Energetic Particle Pitch Angle Distr	Plasma Probe	ISTP (Polar)	6/93

Table 94. Summary Statistics of Instruments Data (Continued)

Instrument	Category	Platform	Launch Date
Fast Plasma Analyzer	Plasma Probe	ISTP (Polar)	6/93
Thermal Ion Dynamics Experiment	Plasma Probe	ISTP (Polar)	6/93
Energetic Particle Acceleration-Composition	Charge And X-Ray Detection	ISTP (Wind)	12/92
Radio And Plasma Waves	Electric Field	ISTP (Wind)	12/92
Magnetic Fields	Magnetometer	ISTP (Wind)	12/92
3-D Plasma Analyzer	Plasma Probe	ISTP (Wind)	12/92
Solar Wind and Suprathermal Ion Composition Studies	Plasma Probe	ISTP (Wind)	12/92
Solar Wind Plasma	Plasma Probe	ISTP (Wind)	12/92
Iue Experiment	Telescope	IUE	1/26/78
United Kingdom Cameras	TV Camera	IUE	1/26/78
Multispectral Scanner (MSS)	High Resolution Mapper	LANDSAT-1	7/23/72
Return Beam Vidicon	TV Camera	LANDSAT-1	7/23/72
Multispectral Scanner (MSS)	High Resolution Mapper	LANDSAT-2	1/22/75
Multispectral Scanner (MSS)	High Resolution Mapper	LANDSAT-3	3/5/78
Return Beam Vidicon	TV Camera	LANDSAT-3	3/5/78
Multispectral Scanner (MSS)	High Resolution Mapper	LANDSAT-4	7/16/82
Thematic Mapper (Tm)	High Resolution Mapper	LANDSAT-4	7/16/82
Multispectral Scanner (MSS)	High Resolution Mapper	LANDSAT-4'	3/1/84
Thematic Mapper (TM)	High Resolution Mapper	LANDSAT-4'	3/1/84
Dual Lens Camera	Film Camera	Lunar Orbiter	8/10/66
Radar System	Active Microwave	Magellan	5/4/89
Scalar Magnetometer	Magnetometer	MAGSAT	10/30/79
Vector Magnetometer	Magnetometer	MAGSAT	10/30/79
Triaxial Fluxgate Magnetometer	Magnetometer	Mariner-10	11/4/73
Solar Plasma Science Probe	Plasma Probe	Mariner-10	11/3/73
Infrared Radiometer	Radiometer	Mariner-10	11/3/73
UV Spectrometer	Spectrometer	Mariner-10	10/3/73
Infrared Interferometer Spectrometer (IRIS)	Interferometer	Mariner-12	Not Launched
Ion Chamber/Particle Flux	Charge and X-Ray Detection	Mariner-3	11/5/64
Trapped Radiation Detector	Charge and X-Ray Detection	Mariner-3	11/5/64
Solar Plasma Probe	Plasma Probe	Mariner-3	11/5/64
Helium Magnetometer	Magnetometer	Mariner-4	10/28/64
Infrared Spectrometer	Interferometer	Mariner-6	2/24/69
UV Spectrometer	Spectrometer	Mariner-6	2/24/69
TV Subsystem	TV Camera	Mariner-6	2/24/69

Table 94. Summary Statistics of Instruments Data (Continued)

Instrument	Category	Platform	Launch Date
Infrared Interferometer Spectrometer (IRIS-M)	Interferometer	Mariner-8	5/8/71
UV Spectrometer	Spectrometer	Mariner-8	5/8/71
TV Subsystem	TV Camera	Mariner-8	5/8/71
Advanced Vidicon Camera System	TV Camera	Nimbus-1	8/28/64
Automatic Picture Transmission System	TV Camera	Nimbus-1	8/28/64
Infrared Interferometer Spectrometer (IRIS-B)	Interferometer	Nimbus-3	4/14/69
Image Dissector Camera System	TV Camera	Nimbus-3	4/14/69
Infrared Interferometer Spectrometer (IRIS-D)	Interferometer	Nimbus-4	4/8/70
Temperature Humidity Ir Radiometer	Radiometer	Nimbus-4	4/8/70
Electrically Scanning Microwave Radiometer	Passive Microwave	Nimbus-5	12/11/72
Surface Composition Mapping Radiometer	Radiometer	Nimbus-5	12/11/72
Electrically Scanning Microwave Radiometer	Passive Microwave	Nimbus-6	6/12/75
Scanning Microwave Spectrometer/Radiometer	Passive Microwave	Nimbus-6	6/12/75
Earth Radiation Budget	Pyrheliometer	Nimbus-6	10/24/78
High Resolution Ir Sounder	Radiometer	Nimbus-6	6/12/75
Limb Radiance Inversion Radiometer	Radiometer	Nimbus-6	6/12/75
Scanning Multichannel Microwave Radiometer	Passive Microwave	Nimbus-7	10/24/78
Coastal Zone Color Scanner (Czcs)	Radiometer	Nimbus-7	10/24/78
Limb Ir Monitoring Of The Stratosphere	Radiometer	Nimbus-7	10/24/78
Stratospheric Aerosol Monitor Ii	Radiometer	Nimbus-7	10/24/78
Solar Backscatter UV/Total Ozone Mapping System	Spectrometer	Nimbus-7	10/24/78
Solar Backscatter Ultraviolet Radiometer 2	Spectrometer	NOAA-F	12/12/84
Advanced Microwave Sounding Unit-A (Amsu-A)	Passive Microwave	NOAA-K	12/93
Wisconsin Experiment Package	Photometer	OAO-2	12/7/68
Celescope Optical Package	Telescope	OAO-2	12/7/68
Wisconsin Experiment Package	Telescope	OAO-2	12/7/68
Princeton Experiment Package	Telescope	OAO-3	8/21/72
Goddard Experiment Package	Spectrometer	OAO-B	11/30/70
Goddard Experiment Package	Telescope	OAO-B	11/30/70
Cosmic Ray Spectra And Fluxes	Charge And X-Ray Detection	OGO-1	9/5/64
Solar Cosmic Rays	Charge And X-Ray Detection	OGO-1	9/5/64
Trapped Radiation Electron Spectrometer	Charge And X-Ray Detection	OGO-1	9/5/64
Rubidium Vapor and Fluxgate Magnetometer	Magnetometer	OGO-1	9/5/64
Triaxial Search Coil Magnetometer	Magnetometer	OGO-1	9/5/64
Atmospheric Mass Magnetic Spectrometer	Mass Measurement	OGO-1	9/5/64

Table 94. Summary Statistics of Instruments Data (Continued)

Instrument	Category	Platform	Launch Date
Gegenschein Photometry	Photometer	OGO-1	9/5/64
Plasma Electrostatic Analyzer	Plasma Probe	OGO-1	9/5/64
Plasma Ion And Electron Trap	Plasma Probe	OGO-1	9/5/64
Plasma Probe (Faraday Cup)	Plasma Probe	OGO-1	9/5/64
Spherical Ion And Electron Trap	Plasma Probe	OGO-1	9/5/64
Low Energy Proton Alpha Measurement	Charge And X-Ray Detection	OGO-2	10/14/65
Solar X-Ray Emissions	Charge And X-Ray Detection	OGO-2	10/14/65
Rubidium Vapor Magnetometer	Magnetometer	OGO-2	10/14/65
Triaxial Search Coil Magnetometer	Magnetometer	OGO-2	10/14/65
Atmospheric Mass Spectrometer	Mass Measurement	OGO-2	10/14/65
Airglow And Auroral Measurements	Photometer	OGO-2	10/14/65
Solar UV Emissions	Spectrometer	OGO-2	10/14/65
Galactic And Solar Cosmic Rays	Charge and X-Ray Detection	OGO-4	7/28/67
Lyman Alpha And UV Airglow Experiment	Charge and X-Ray Detection	OGO-4	7/28/67
Charged Particle Detector	Charge and X-Ray Detection	OGO-5	3/4/68
Cosmic Ray Electrons	Charge and X-Ray Detection	OGO-5	3/4/68
Electron And Proton Spectrometer	Charge and X-Ray Detection	OGO-5	3/4/68
Energetic Radiation From Solar Flares	Charge and X-Ray Detection	OGO-5	3/4/68
Low Energy Heavy Cosmic Ray Particles	Charge and X-Ray Detection	OGO-5	3/4/68
Measurement Of Absolute Flux And Energy	Charge and X-Ray Detection	OGO-5	3/4/68
Plasma Wave Detector	Electric Field	OGO-5	3/4/68
Triaxial Fluxgate Magnetometer	Magnetometer	OGO-5	3/4/68
Light Ion Mass Magnetic Spectrometer	Mass Measurement	OGO-5	3/4/68
UV Photometer Experiment	Photometer	OGO-5	3/4/68
Solar And Galactic Cosmic Rays	Charge and X-Ray Detection	OGO-6	6/5/69
Trapped And Precipitating Electrons	Charge and X-Ray Detection	OGO-6	6/5/69
Triaxial Search Coil Magnetometer	Magnetometer	OGO-6	6/5/69
Neutral Atmosphere Composition Experiment	Mass Measurement	OGO-6	6/5/69
Electron Temperature And Density	Plasma Probe	OGO-6	6/5/69
Solar UV Emissions	Spectrometer	OGO-6	6/5/69
EUV Spectrometer/Spectroheliograph	Spectroheliograph	OSO-2	2/3/65
Gamma Ray Telescope	Charge and X-Ray Detection	OSO-3	3/8/67
Particle and Gamma Ray Telescope	Charge and X-Ray Detection	OSO-3	3/8/67
X-Ray Telescope	Charge and X-Ray Detection	OSO-3	3/8/67
UV Spectrometer	Spectrometer	OSO-3	3/8/67

Table 94. Summary Statistics of Instruments Data (Continued)

Instrument	Category	Platform	Launch Date
Hydrogen Lyman Alpha Telescope	Charge and X-Ray Detection	OSO-4	10/18/67
Solar X-Ray Spectrometer	Charge and X-Ray Detection	OSO-4	10/18/67
X-Ray Monitor	Charge and X-Ray Detection	OSO-4	10/18/67
UV Spectroheliometer	Spectroheliograph	OSO-4	10/18/67
Solar X-Ray Ion Chamber Photometer	Charge And X-Ray Detection	OSO-5	1/22/69
Zodiacal Light Monitor	Photometer	OSO-5	1/22/69
EUV Spectroheliograph	Spectroheliograph	OSO-5	1/22/69
Solar EUV Monitor	Spectrometer	OSO-5	1/22/69
High Energy Neutron Detector	Charge and X-Ray Detection	OSO-6	8/9/69
X-Ray Burst and Mapping	Charge and X-Ray Detection	OSO-6	8/9/69
Zodiacal Light Polarimeter	Photometer	OSO-6	8/9/69
UV Spectroheliograph	Spectroheliograph	OSO-6	8/9/69
Celestial Cosmic Rays	Charge and X-Ray Detection	OSO-7	9/29/71
Cosmic X-Rays	Charge and X-Ray Detection	OSO-7	9/29/71
Solar Gamma Ray Monitor	Charge and X-Ray Detection	OSO-7	9/29/71
White Light and EUV Coronagraph	Photometer	OSO-7	9/29/71
EUV And X-Ray Spectroheliograph	Spectroheliograph	OSO-7	9/29/71
EUV And X-Ray Spectroheliograph	Telescope	OSO-7	9/29/71
Cosmic X-Ray Spectroscopy	Charge and X-Ray Detection	OSO-8	6/21/75
High Energy Celestial X-Rays	Charge and X-Ray Detection	OSO-8	6/21/75
Mapping X-Ray Heliometer	Charge and X-Ray Detection	OSO-8	6/21/75
Soft X-Ray Background Radiation	Charge and X-Ray Detection	OSO-8	6/21/75
Stellar And Solar X-Radiation	Charge and X-Ray Detection	OSO-8	6/21/75
Extreme Ultraviolet Emissions	Photometer	OSO-8	6/21/75
UV Spectrometer	Spectrometer	OSO-8	6/21/75
Solar Flare X-Ray Polarimeter Experiment	Charge and X-Ray Detection	OSS-1	3/22/82
Thermal Canister	Miscellaneous	OSS-1	3/22/82
Vehicle Charging And Potential Experiment	Miscellaneous	OSS-1	3/22/82
Shuttle/Spacelab Induced Atmosphere (SSIA)	Photometer	OSS-1	3/22/82
Solar UV Spectral Irradiance Monitor (S'JSIM)	Spectrometer	OSS-1	3/22/82
Shuttle Imaging Radar-A (SIR-A)	Active Microwave	OSTA-1	11/12/81
Feature Identification And Location Experiment	Miscellaneous	OSTA-1	11/21/81
Measurement Of Air Pollution From Satellites	Radiometer	OSTA-1	11/12/81
Ocean Color Experiment	Radiometer	OSTA-1	11/12/81
Shuttle Multispectral Ir Radiometer	Radiometer	OSTA-1	11/12/81

Table 94. Summary Statistics of Instruments Data (Continued)

Instrument	Category	Platform	Launch Date
Shuttle Imaging Radar-B (SIR-B)	Active Microwave	OSTA-3	10/5/84
Cloud Particle Size Spectrometer	Laser	Pioneer Venus	5/20/78
Geiger Tube Telescope	Charge and X-Ray Detection	Pioneer-10	3/3/72
Trapped Radiation Telescope	Charge and X-Ray Detection	Pioneer-10	3/3/72
Cosmic Ray Detector	Charge and X-Ray Detection	Pioneer-6	12/16/65
Cosmic Ray Gradient Detector	Charge and X-Ray Detection	Pioneer-8	12/13/67
Stratospheric Aerosol And Gas Experiment I	Spectrometer	Sage	2/18/79
Electric Field Instrument	Electric Field	San Marco-D	11/85
X-Ray Experiment	Charge and X-Ray Detection	SAS-1	12/12/70
X-Ray Experiment	Charge and X-Ray Detection	SAS-3	5/7/75
Radar Altimeter	Active Microwave	SEASAT-1	6/27/78
Scatterometer	Active Microwave	SEASAT-1	6/27/78
Synthetic Aperature Radar (SAR)	Active Microwave	SEASAT-1	6/27/78
Windsat	Laser	Shuttle	Not Launched
Altimeter (S-193)	Active Microwave	Skylab	5/14/73
Scatterometer (S-193)	Active Microwave	Skylab	5/14/73
Cit Photoheliograph Film Camera	Film Camera	Skylab	Not Flown
Extreme UV Spectroheliograph Film Camera (S082a)	Film Camera	Skylab	5/14/73
Multispectral Film Camera (S190a)	Film Camera	Skylab	5/14/73
Spectrograph and EUV Monitor Film Camera (S082b)	Film Camera	Skylab	5/14/73
White Light Coronograph Film Camera (S052)	Film Camera	Skylab	5/14/73
X-Ray Spectrographic Telescope Film Camera (S054)	Film Camera	Skylab	5/14/73
L-Band Microwave Radiometer (S-194)	Passive Microwave	Skylab	5/14/73
Microwave Radiometer (S-193)	Passive Microwave	Skylab	5/14/73
Contamination Measurement (T027)	Photometer	Skylab	5/14/73
Coronagraph Contamination Measurement (T025)	Photometer	Skylab	5/14/73
White Light Coronagraph (S052)	Photometer	Skylab	5/14/73
Multispectral Scanner S-192	Radiometer	Skylab	5/14/73
Cit Photoheliograph	Spectroheliograph	Skylab	Not Launched
EUV Spectrograph (S082b)	Spectroheliograph	Skylab	5/14/73
UV Scanning Polychromator/Spectroheliometer	Spectroheliograph	Skylab	5/14/73
XUV Spectroheliograph (S082a)	Spectroheliograph	Skylab	5/14/73
EUV Spectrograph (S082b)	Spectrometer	Skylab	5/14/73
Cit Photoheliograph	Telescope	Skylab	Not Launched
Hydrogen Alpha Telescope	Telescope	Skylab	5/14/73

Table 94. Summary Statistics of Instruments Data (Continued)

Instrument	Category	Platform	Launch Date
White Light Coronograph TV Camera (S052)	TV Camera	Skylab	5/14/73
UV Spectrometers	Spectrometer	SME	10/6/81
Gamma Ray Spectrometer	Charge and X-Ray Detection	SMM	2/14/80
Hard X-Ray Burst Spectrometer	Charge and X-Ray Detection	SMM	2/14/80
Hard X-Ray Imaging Spectrometer	Charge and X-Ray Detection	SMM	2/14/80
X-Ray Polychromator	Charge and X-Ray Detection	SMM	2/14/80
White Light Coronagraph/Polarimeter (WLCP)	Photometer	SMM	2/14/80
Active Cavity Irradiance Monitor (ACRIM)	Pyrheliometer	SMM	2/14/80
Ultraviolet Spectrometer and Polarimeter	Spectrometer	SMM	2/14/80
Visible and Infrared Spin-Scan Radiometer (VISSR)	Radiometer	SMS-1	5/17/74
Space Laser Communications System	Laser	SPACE TEST	Not Launched
Atmospheric Lidar Multi-User Instrument	Laser	SPACELAB	Not Launched
Infrared Heterodyning Radiometer	Laser	SPACELAB	Not Launched
Laser Absorption Spectrometer	Laser	SPACELAB	Not Launched
Atmospheric Emissions Photographic Imaging	Miscellaneous	SPACELAB-1	11/28/83
Space Experiments With Particle Accelerators	Miscellaneous	SPACELAB-1	11/28/83
Imaging Spectrometric Observatory (Iso)	Spectrometer	SPACELAB-1	11/28/83
Far Ultraviolet Space Telescope	Telescope	SPACELAB-1	11/28/83
Cosmic Ray Nuclei Experiment (Crne)	Charge And X-Ray Detection	SPACELAB-2	7/29/85
High Resolution Telescope And Spectrograph	Spectroheliograph	SPACELAB-2	7/29/85
Solar UV Spectral Irradiance Monitor (Susim)	Spectrometer	SPACELAB-2	7/29/85
Small Helium-Cooled Infrared Telescope	Telescope	SPACELAB-2	7/29/85
Solar Magnetic And Velocity Field Measurement	Telescope	SPACELAB-2	7/29/85
Wide Field And Planetary Camera (Wf/Pc)	Miscellaneous	ST	3/26/90
High Speed Photometer (HSP)	Photometer	ST	3/26/90
Faint Object Spectrograph (FOS)	Spectrometer	ST	3/26/90
High Resolution Spectrograph (HRS)	Spectrometer	ST	3/26/90
Optical Telescope Assembly	Telescope	ST	3/26/90
Advanced Vidicon Camera System	TV Camera	Tiros-M	1/23/70
Automatic Picture Transmission System	TV Camera	Tiros-M	1/23/70
Space Environment Monitor (SEM)	Charge and X-Ray Detection	Tiros-N	6/16/78
Tovs Microwave Sounding Unit	Passive Microwave	Tiros-N	6/16/78
Advanced Very High Resolution Radiometer	Radiometer	Tiros-N	6/16/78
High Resolution Ir Sounder/2	Radiometer	Tiros-N	6/16/78
High Resolution Doppler Imager (HRDI)	Interferometer	UARS	11/27/91

Table 94. Summary Statistics of Instruments Data (Continued)

Instrument	Category	Platform	Launch Date
Microwave Limb Sounder (MLS)	Passive Microwave	UARS	11/27/91
Active Cavity Irradiance Monitor II (ACRIM II)	Pyrheliometer	UARS	11/27/91
Halogen Occultation Experiment (HALOE)	Radiometer	UARS	11/17/91
Crygenic Limb Array Etalon Spectrometer (CLAES)	Spectrometer	UARS	11/27/91
Solar Stellar Irradiance Comparison Experiment	Spectrometer	UARS	11/27/91
Solar UV Spectral Irradiance Monitor (SUSIM)	Spectrometer	UARS	11/27/91
Upper Atmosphere Mass Spectrometer	Mass Measurement	Viking Lander	8/20/75
Infrared Thermal Mapper	Radiometer	Viking Orbiter	8/20/75
Visual Imaging System	TV Camera	Viking Orbiter	8/20/75
Cosmic Ray Telescope	Charge and X-Ray Detection	Voyager-1	9/5/77
Low Energy Charged Particle Detector	Charge and X-Ray Detection	Voyager-1	9/5/77
Plasma Wave Receiver	Electric Field	Voyager-1	9/5/77
Infrared Interferometer Spectrometer (IRIS)	Interferometer	Voyager-1	9/5/77
Triaxial Fluxgate Magnetometer	Magnetometer	Voyager-1	9/5/77
Photopolarimeter	Photometer	Voyager-1	9/5/77
Plasma Detector	Plasma Probe	Voyager-1	9/5/77

Table 95. Summary Statistics of Photometer Data

	N	Minimum	Median	Mean	Maximum
DDT&E Cost (1990$M)	24	0.50	3.86	6.67	30.39
Flight Cost (1990$M)	24	0.17	1.32	2.35	11.89
Weight (lbs)	25	5.51	33.00	107.99	590.00
Volume (ft3)	15	0.10	1.41	13.00	87.00
Data Rate (Bps)	7	8.00	1040.00	40818.29	256000.00
Average Input Power (watts)	18	1.68	5.50	26.66	210.80
Spectral Range, minimum (Å)	19	40.00	1200.00	1778.95	4100.00
Spectral Range, maximum (Å)	19	584.00	6300.00	26612.47	420000.00
Spectral range, delta (Å)	19	280.00	2583.00	24833.53	415900.00
Diameter of Primary Optics (in.)	10	0.90	3.22	4.92	16.00
Field of View (deg.)	11	0.50	6.00	32.38	180.00

2. Spectrometers

A spectrometer consists of a spectroscope for producing a spectrum combined with a calibrated scale for measuring wavelength. A spectrograph uses a photographic camera to record the spectrum produced. A scanning spectrometer produces only designated regions of the spectrum for observation. The SICM data base contains 29 instruments in the spectrometer category.

Table 96. Summary Statistics of Spectrometer Data

	N	Minimum	Median	Mean	Maximum
DDT&E Cost (1990$M)	29	0.87	5.43	12.04	48.60
Flight Cost (1990$M)	29	0.29	2.00	4.28	20.18
Weight (lbs)	29	8.80	65.80	216.36	1226.00
Volume (ft3)	22	0.18	3.00	17.49	189.05
Data Rate (Bps)	22	30.00	710.00	2210.50	11520.00
Average Input Power (watts)	25	2.10	15.68	35.00	165.00
Spectral Range, minimum (Å)	5	8.40	20.00	29.18	60.00
Spectral Range, maximum (Å)	27	160.00	1150.00	1479.04	7000.00
Spectral range, delta (Å)	27	1030.00	4000.00	11323.11	127000.00
Pointing Accuracy (arc-sec)	27	750.00	2800.00	9844.07	123500.00
Grating Ruling (lines/mm)	9	0.03	10.00	236.89	1800.00
Units per Measurement	9	1200.00	2400.00	2882.22	6000.00

3. Spectroheliographs

A spectroheliograph is used to photograph the sun or other stars in one spectral band. Also included in this category are spectroheliometers, for examining various spectrums, and photoheliographs, which are refracting telescopes for photographing the sun's disk. Ten instruments are listed in the data base.

Table 97. Summary Statistics of Spectroheliograph Data

	N	Minimum	Median	Mean	Maximum
DDT&E Cost (1990$M)	10	3.00	11.53	20.20	48.60
Flight Cost (1990$M)	10	1.28	3.46	5.74	12.97
Weight (lbs)	10	26.15	169.98	299.91	895.38
Volume (ft^3)	10	0.30	12.40	20.66	69.04
Average Input Power (watts)	8	1.20	7.90	57.43	340.00
Spectral Range, minimum (Å)	10	150.00	300.00	615.00	2000.00
Spectral Range, maximum (Å)	10	335.00	1325.00	2004.10	7000.00
Spectral range, delta (Å)	10	185.00	1000.00	1389.10	5000.00
Spectral Resolution (Å)	9	0.05	0.20	0.84	3.00
Diameter of Primary Lens (in.)	4	1.60	6.80	10.20	25.60

4. Telescopes

Telescopes use a system of lenses and/or mirrors to collect electromagnetic radiation from the infrared to the x-ray regions with increased resolution or intensity. This category includes four common, two-mirror telescope designs: Cassegrain, Gregorian, Ritchy-Cretien, and Schwarzschild telescopes. In addition, grazing incidence telescopes used to form images of celestial x-ray or gamma-ray sources are included in this category. There are 23 data points in the telescope data base.

Table 98. Summary Statistics of Telescope Data

	N	Minimum	Median	Mean	Maximum
DDT&E Cost (1990$M)	23	0.95	11.67	40.10	455.40
Flight Cost (1990$M)	23	0.32	3.66	16.73	192.77
Weight (lbs)	23	23.60	527.00	1107.84	9033.30
Volume (ft^3)	16	1.28	57.94	202.67	2265.70
Data Rate (Bps)	5	30.00	4075.00	10521.00	40960.00
Average Input Power (watts)	13	8.80	35.00	57.37	155.00
Spectral Range, minimum (Å)	14	3.00	1150.00	10197.71	85000.00
Spectral Range, maximum (Å)	14	62.00	3750.00	97679.43	1200000
Spectral range, delta (Å)	14	59.00	2100.00	87481.71	1160000
Primary Mirror Diameter (in.)	17	2.00	16.00	21.72	94.50
Spectral Resolution (Å)	8	0.10	3.50	6.90	32.00
Angular Resolution (arc-sec)	10	0.01	5.50	9.40	35.00
Focal Length (in.)	9	10.00	31.90	68.49	216.50

5. Interferometers

Interferometers obtain information in terms of wavelength based on an analysis of interference. In an interferometer, light from a source is split into two or more beams, which are subsequently reunited after traveling over different paths and display interference. Nine instruments of this category are in the SICM data base.

Table 99. Summary Statistics of Interferometer Data

	N	Minimum	Median	Mean	Maximum
DDT&E Cost (1990$M)	9	2.86	7.92	12.23	42.92
Flight Cost (1990$M)	9	0.96	2.32	3.25	8.81
Weight (lbs)	9	30.70	42.00	117.94	426.60
Volume (ft3)	7	0.50	1.95	5.16	12.88
Data Rate (Bps)	7	781.00	1330.00	2251.57	4750.00
Average Input Power (watts)	8	4.00	15.00	34.38	109.00
Spectral Range, minimum (Å)	9	4000.00	25000.00	83219.67	500000
Spectral Range, maximum (Å)	9	7330.00	330000.00	1.135E+7	1.00E+8
Spectral range, delta (Å)	9	1753.00	310000.00	1.127E+7	9.95E+7
Field of View (deg.)	6	0.25	4.75	4.46	8.00
Pointing Resolution (cm)	6	1000.00	1100.00	1333.33	2000.00
Mirror Travel (mm)	4	1.38	2.83	2.83	4.26
Mirror Travel rate (mm/sec)	4	0.04	0.23	0.19	0.27
Detector Size (mm)	6	1.50	2.75	23.38	100.00
Operating Temperature (K)	6	2.00	215.00	182.00	290.00

6. Radiometers

Radiometers are concerned with the detection and measurement of radiant electromagnetic energy, especially in the infrared region. There are 23 radiometer data points.

Table 100. Summary Statistics of Radiometer Data

	N	Minimum	Median	Mean	Maximum
DDT&E Cost (1990$M)	23	1.67	7.15	11.83	47.03
Flight Cost (1990$M)	23	0.59	2.01	3.64	13.00
Weight (lbs)	23	7.20	90.00	117.38	351.00
Volume (ft3)	21	0.12	2.84	6.35	22.00
Data Rate (Bps)	14	16.00	4000.00	200126.36	1.00E+6
Average Input Power (watts)	19	3.00	25.00	38.86	180.00
Spectral Range, minimum (Å)	23	0.20	0.69	1.98	8.50
Spectral Range, maximum (Å)	23	0.80	12.50	49.48	500.00
Spectral range, delta (Å)	23	0.04	12.05	47.50	499.70
Primary Mirror Diameter (in)	16	1.00	7.25	8.68	24.00
Scan Angle (deg)	10	18.00	50.00	58.80	150.00
Number of Spectral Bands	21	1.00	4.00	7.33	24.00

7. High Resolution Mappers

These instruments are generally used to produce high resolution images of the earth's surface based on the analysis of multiple energy bands. Although similar in construction to radiometers, high resolution mappers require greater accuracy and, in turn, are more complex. There are seven data points in the sample.

Table 101. Summary Statistics of High Resolution Mapper Data

	N	Minimum	Median	Mean	Maximum
DDT&E Cost (1990$M)	4	35.13	62.07	79.04	156.90
Flight Cost (1990$M)	7	10.59	11.89	17.34	31.47
Weight (lbs)	7	124.20	126.40	254.27	568.80
Volume (ft3)	7	7.42	7.42	21.99	54.66
Data Rate (Bps)	7	15.00	15.00	35.00	85.00
Average Input Power (watts)	7	42.00	42.00	123.29	320.00
Spectral Range, minimum (Å)	7	0.45	0.50	0.49	0.50
Spectral Range, maximum (Å)	7	1.10	1.10	6.00	12.60
Spectral range, delta (Å)	7	0.60	0.60	5.51	12.10
Number of Spectral Bands	7	4.00	4.00	5.00	7.00

8. Magnetometers

Magnetometers measure the magnitude and the direction of a magnetic field. There are three types of magnetometers: search coil, fluxgate, and atomic nuclei. Of the three, the atomic nuclei type is the most expensive. Five of the twenty-four data points are of this type. There are 24 magnetometer data points.

Table 102. Summary Statistics of Magnetometer Data.

	N	Minimum	Median	Mean	Maximum
DDT&E Cost (1990$M)	24	0.38	1.40	1.85	5.02
Flight Cost (1990$M)	24	0.16	0.68	1.03	2.54
Weight (lbs)	24	1.35	7.41	10.84	40.79
Volume (ft3)	9	111.25	383.00	589.89	1940.00
Data Rate (Bps)	16	128.00	618.00	8710.50	64000.00
Average Input Power (watts)	22	0.60	4.29	4.83	21.96
Number of Sensors	19	1.00	3.00	3.11	6.00
Units per Experiment	17	1.00	1.00	1.29	3.00

9. Electric Field Instruments

A category of instruments used to examine direct current (DC) and very low frequency alternating current (VLF AC) electric fields. There are 13 data points.

Table 103. Summary Statistics of Electric Field Instrument Data

	N	Minimum	Median	Mean	Maximum
DDT&E Cost (1990$M)	13	0.11	1.21	1.58	3.09
Flight Cost (1990$M)	13	0.09	0.82	1.27	2.53
Weight (lbs)	13	1.70	17.86	22.72	70.28
Data Rate (Bps)	8	16.00	1536.00	1379.38	2520.00
Average Input Power (watts)	10	3.70	6.85	9.62	22.91
Frequency Range, min. (khz)	11	0.00	0.00	0.05	0.30
Frequency Range, max. (khz)	11	0.06	178.00	6514.47	65000.00
Frequency Range, delta (khz)	11	0.06	178.00	6514.42	65000.00
Number of Antennas	9	1.00	2.00	2.11	3.00
Number of Sensors	7	1.00	2.00	2.71	6.00

10. Charge and X-Ray Detection Instruments

This category of instruments, which contains eighty-one examples, is used to detect x-rays and/or cosmic ray particles in the solar wind.

Table 104. Summary Statistics of Charge and X-Ray Detection Instrument Data

	N	Minimum	Median	Mean	Maximum
DDT&E Cost (1990$M)	81	0.55	2.54	5.95	57.95
Flight Cost (1990$M)	81	0.22	1.03	2.59	36.53
Weight (lbs)	82	2.20	29.86	336.51	5256.00
Volume (ft3)	28	11.15	1125.00	37871.20	387828.00
Data Rate (Bps)	40	13.00	1150.00	8190.00	128000.00
Average Input Power (watts)	57	0.91	6.00	27.82	331.00
Energy Range, minimum (EV)	70	0.00	0.00	2104.91	50000.00
Energy Range, Maximum (EV)	70	0.15	6000.00	2.91E+10	2.00E+12
Energy Range, delta (EV)	70	0.03	5790.00	2.91E+10	2.00E+12
Units per Experiment	47	1.00	1.00	1.98	10.00
Number of Detectors	60	1.00	4.00	5.32	40.00

11. Mass Measurement Instruments

A type of instrument used to determine the composition and concentration of particle matter in the atmosphere or on the surface of the planets. There are 18 data points in this sample.

Table 105. Summary Statistics of Mass Measurement Instrument Data

	N	Minimum	Median	Mean	Maximum
DDT&E Cost (1990$M)	18	0.40	1.33	2.73	9.80
Flight Cost (1990$M)	18	0.36	0.55	1.15	4.20
Weight (lbs)	18	6.00	16.69	17.39	33.07
Volume (ft3)	14	296.00	761.70	771.74	1172.50
Data Rate (Bps)	10	32.00	910.00	7125.60	64000.00
Average Input Power (watts)	17	1.00	8.95	10.59	29.30

12. Plasma Probes

Plasma probes measure the energy and temperature of free electrons and protons in free space. There are 30 data points in the data base.

Table 106. Summary Statistics of Plasma Probes Data

	N	Minimum	Median	Mean	Maximum
DDT&E Cost (1990$M)	30	0.49	1.37	1.95	8.06
Flight Cost (1990$M)	30	0.20	0.68	0.84	3.45
Weight (lbs)	30	3.25	13.25	16.58	37.26
Volume (ft3)	11	144.00	324.00	490.25	1171.98
Data Rate (Bps)	18	32.00	902.00	1524.44	6656.00
Average Input Power (watts)	24	1.70	6.80	6.89	15.32
Energy Range, minimum (EV)	23	0.00	0.01	0.97	20.00
Energy Range, Maximum (EV)	23	1.00	50.00	1098.61	17000.00
Energy Range, delta (EV)	23	1.00	49.95	1097.64	16980.00
Units per Experiment	17	1.00	1.00	1.76	6.00

13. Active Microwave Instruments

Instruments of this type employ the principles of radar with microwave transmissions. The instruments are more commonly referred to as radar altimeters, Scatterometers, and synthetic aperture radar. There are 9 data points in the sample.

Table 107. Summary Statistics of Active Microwave Instruments Data

	N	Minimum	Median	Mean	Maximum
DDT&E Cost (1990$M)	9	7.58	14.88	20.94	63.00
Flight Cost (1990$M)	9	3.24	4.96	8.85	33.84
Weight (lbs)	9	150.00	258.00	441.72	1120.00
Volume (ft3)	6	4.20	9.50	249.98	785.00
Data Rate (Bps)	8	0.50	379.25	19597.44	110000.00
Average Input Power (watts)	6	72.00	198.50	384.17	1145.00
Bandwidth/Pulsewidth (MHz)	5	2.30	14.00	72.26	320.00
Frequency/Pulse Rate (GHz)	6	1.28	1.84	5.72	14.60

14. Passive Microwave Instruments

Passive microwave instruments are really microwave radiometers in that they measure the intensity of microwave energy at a particular time from a particular pointing angle.

Table 108. Summary Statistics of Passive Microwave Instruments Data

	N	Minimum	Median	Mean	Maximum
DDT&E Cost (1990$M)	11	5.16	8.97	14.42	43.54
Flight Cost (1990$M)	11	1.21	3.19	4.73	15.50
Weight (lbs)	11	17.00	100.00	163.56	624.00
Volume (ft3)	6	0.20	3.30	35.02	191.90
Data Rate (Bps)	8	120.00	825.00	2077.50	10000.00
Average Input Power (watts)	9	10.00	60.00	74.72	169.00
Field of View (deg)	7	0.25	10.00	15.77	48.00

15. Lasers

These instruments employ the principles of laser radar and are particularly effective for short ranges. There are seven data points in the sample.

Table 109. Summary Statistics of Laser Data

	N	Minimum	Median	Mean	Maximum
DDT&E Cost (1990$M)	7	3.11	10.05	28.11	71.98
Flight Cost (1990$M)	7	0.96	3.71	11.51	30.85
Weight (lbs)	7	9.60	230.00	820.09	3125.00
Volume (ft^3)	4	0.29	2.92	4.71	12.70
Average Input Power (watts)	7	20.00	1000.00	1083.57	2346.00
Range (km)	4	68.00	203.50	192.75	296.00

16. Pyrheliometer

Pyrheliometers measure the total intensity of direct solar radiation. The data base contains four data points.

Table 110. Summary Statistics of Pyrheliometer Data

	N	Minimum	Median	Mean	Maximum
DDT&E Cost (1990$M)	4	4.20	8.44	8.09	11.28
Flight Cost (1990$M)	4	1.80	3.62	3.53	5.07
Weight (lbs)	4	22.30	61.03	56.29	80.80

17. Film Cameras

This class covers the standard film mapping and panoramic cameras. The database contains ten data points.

Table 111. Summary Statistics of Film Camera Data

	N	Minimum	Median	Mean	Maximum
DDT&E Cost (1990$M)	10	1.16	5.21	8.76	19.68
Flight Cost (1990$M)	10	0.29	1.05	1.29	2.78
Weight (lbs)	10	19.00	56.50	109.81	321.00
Volume (ft^3)	10	0.23	1.74	3.92	12.89
Average Input Power (watts)	4	56.00	100.00	126.50	250.00

18. Television Cameras

This class covers the full range of television cameras for real time transmission or magnetic tape storage. There are 17 TV cameras in the data base.

Table 112. Summary Statistics of Television Camera Data

	N	Minimum	Median	Mean	Maximum
DDT&E Cost (1990$M)	17	3.37	7.34	10.59	42.37
Flight Cost (1990$M)	17	0.84	2.42	2.73	8.96
Weight (lbs)	17	7.00	46.00	57.25	196.00
Volume (ft3)	13	0.20	1.28	2.69	11.20
Average Input Power (watts)	17	9.00	20.00	36.12	172.00
Spectral Range, minimum (Å)	14	1150.00	4500.00	4217.86	5300.00
Spectral Range, maximum (Å)	14	3200.00	6500.00	6500.00	8300.00
Spectral range, delta (Å)	14	1000.00	2125.00	2282.14	3550.00
Number of Active Scan Lines	14	620.00	816.50	1311.21	4125.00

APPENDIX A

NASA NEW START INFLATION INDEX

APPENDIX A

NASA NEW START INFLATION INDEX

Table A-1. NASA New Start Inflation Index

From	To 1990
1959	6.280
1960	6.021
1961	5.834
1962	5.610
1963	5.420
1964	5.187
1965	5.016
1967	4.732
1967	4.511
1968	4.280
1969	4.049
1970	3.788
1971	3.563
1972	3.371
1973	3.189
1974	2.975
1975	2.685
1976	2.463
TQ	2.413
1977	2.224
1978	2.063
1979	1.884
1980	1.702
1981	1.546
1982	1.434
1983	1.348
1984	1.279
1985	1.236
1986	1.200
1987	1.153
1988	1.095
1989	1.045
1990	1.000

Source: NASA Comptroller, May 1991.

APPENDIX B

CHRONICLE OF U.S. UNMANNED SPACECRAFT BY CATEGORY

APPENDIX B

CHRONICLE OF U.S. UNMANNED SPACECRAFT BY CATEGORY

This appendix contains a list of U.S. unmanned spacecraft and their launch dates arranged by type, program, and launch date.

Table B-1. Scientific and Technology Satellites

Spacecraft	Launch Date	Reentry Date	Comments
Vanguard: Small technology satellite sponsored by the U.S. Navy			
Vanguard-TV0	12/08/56		Sub-orbital; no payload
Vanguard-TV1	05/01/57		Sub-orbital; no payload
Vanguard-TV2	10/23/57		Sub-orbital; no payload
Vanguard-TV3	12/06/57		Failed to orbit
Vanguard-TV3BU	02/05/58		Failed to orbit
Vanguard-1	03/17/58		
Vanguard-TV5	04/28/58		Failed to orbit
Vanguard SLV-1	05/27/58		Failed to orbit
Vanguard SLV-2	06/26/58		Failed to orbit
Vanguard SLV-3	09/26/58		Failed to orbit
Vanguard-2	02/17/59		
Vanguard SLV-5	04/13/59		Failed to orbit
Vanguard SLV-6	06/22/59		Failed to orbit
Vanguard-3	09/18/59		
Explorer: Various science programs sponsored by the U.S. Army and NASA			
Explorer-1	01/31/58	03/31/70	
Explorer-2	03/05/58		Failed to orbit
Explorer-3	03/26/58	06/28/58	
Explorer-4	07/26/58	10/23/59	
Explorer-5	08/24/58		Failed to orbit
Explorer-S1	07/16/59		Failed to orbit
Explorer-6	08/07/59	07/15/61	
Explorer-7	10/13/59		
Explorer-S46	03/23/60		Failed to orbit
Explorer-8	11/03/60		
Explorer-S56	12/04/60		Failed to orbit
Explorer-9	02/16/61	04/09/64	
Explorer-S45	02/24/61		Failed to orbit
Explorer-10	03/25/61		
Explorer-11	04/27/61		
Explorer-S45A	05/24/61		Failed to orbit
Explorer-S55	06/30/61		Failed to orbit

Table B-1. Scientific and Technology Satellites (Continued)

Spacecraft	Launch Date	Reentry Date	Comments
Explorer-12	08/15/61		
Explorer-13	08/25/61	08/28/61	
Explorer-14	10/02/62	07/01/66	
Explorer-15	10/27/62	02/19/83	
Explorer-16	12/16/62		
Explorer-17	04/02/63	01/24/66	AE-1
Explorer-18	11/26/63	02/15/65	
Explorer-19	12/19/63	05/10/81	
Explorer-S66	03/19/64		Failed to orbit
Explorer-20	08/25/64		
Explorer-21	10/03/64	01/15/66	IMP-B
Explorer-22	10/09/64		
Explorer-23	11/06/64	06/29/83	
Explorer-24	11/21/64	10/18/68	
Explorer-25	11/21/64		
Explorer-26	12/21/64		
Explorer-27	04/29/65		
Explorer-28	05/29/65	07/04/68	IMP-C
Explorer-29	11/06/65		GEOS-1
Explorer-30	11/19/65		Solrad-8
Explorer-31	11/28/65		
Explorer-32	05/25/66	02/22/85	AE-2
Explorer-33	07/01/66		IMP-D
Explorer-34	05/24/67	05/03/69	IMP-F
Explorer-35	07/19/67		IMP-E
Explorer-36	01/11/68		GEOS-2
Explorer-37	03/05/68		Solrad-9
Explorer-38	07/04/68		RAE-1
Explorer-39	08/08/68	06/22/81	
Explorer-40	08/08/68		
Explorer-41	06/21/69	02/23/72	IMP-G
Explorer-42	12/12/70	04/05/79	SAS-1 or Uhuru
Explorer-43	03/13/71	10/02/74	IMP-I
Explorer-44	07/08/71	02/15/79	Solrad-1
Explorer-45	11/15/71		Magnetospheric studies
Explorer-46	08/13/72	01/02/79	MTS
Explorer-47	09/23/72		IMP-H
Explorer-48	11/15/72	05/01/79	SAS-2
Explorer-49	06/10/73		RAE-2
Explorer-50	10/25/73		IMP-J
Explorer-51	12/13/73	02/12/78	AE-3
Explorer-52	06/03/74	04/28/78	Hawkeye
Explorer-53	05/07/75	04/09/79	SAS-3
Explorer-54	10/06/75	03/12/76	AE-4
Explorer-55	11/20/75	06/10/81	AE-5
Beacon: Satellites for ionospheric studies			
Beacon-1	10/23/58		Failed to orbit
Beacon-2	08/14/59		Failed to orbit

Table B-1. Scientific and Technology Satellites (Continued)

Spacecraft	Launch Date	Reentry Date	Comments
Solrad: U.S. Navy satellites to investigate solar radiation. Also referred to as Sunray or Galactic Radiation Experiment Background			
Solrad-1	06/22/60		
Solrad-2	11/30/60		Failed to orbit
Solrad-3	06/29/61		Failed to separate from Injun-1
Solrad-4A	01/24/62		Failed to orbit
Solrad-4B	04/26/62		Failed to orbit
Solrad-5A			No data
Solrad-5B	01/11/64		
Solrad-6A	06/15/63	08/01/63	
Solrad-6B	03/09/65		Ferret-12
Solrad-7A	01/11/64		
Solrad-7B	03/09/65		
Solrad-8	11/19/65		Explorer-30
Solrad-9	03/05/68		Explorer-37
Solrad-10	07/08/71	12/15/79	Explorer-44
Solrad-11A	03/15/76		
Solrad-11B	03/15/76		
Lofti: Low Frequency Trans Ionospheric satellites			
Lofti-1	02/21/61	03/30/61	
Lofti	01/24/62		Failed to orbit
Lofti-2	06/15/63	07/18/63	
Injun: Magnetosphere investigation			
Injun-1	06/29/61		Failed to separate from Solrad 3
Injun-2	01/24/62		Failed to orbit
Injun-3	12/12/62	08/25/68	
Injun-4	11/21/64		Explorer-25
Injun-5	08/08/68		Explorer-40
OSO: Orbiting Solar Observatory			
OSO-1	03/07/62	10/08/81	
OSO-2	02/03/65		
OSO-C	08/25/65		Failed to orbit
OSO-3	03/08/67	04/04/82	
OSO-4	10/18/67	06/15/82	
OSO-5	01/22/69	04/02/84	
OSO-6	08/09/69	03/07/81	
OSO-7	09/29/71	07/09/74	
OSO-8	06/21/75	07/09/86	
ERS: Environmental Research Satellite sponsored by the U.S. Air Force			
ERS-1	04/12/62		Failed to orbit
ERS-2	09/17/62	01/16/62	TRS
ERS-3	12/17/62		Failed to orbit
ERS-4	12/17/62		Failed to orbit
ERS-5	05/09/63		DASH-1 or TRS-2
ERS-6	05/09/63		TRS-3
ERS-7	06/12/63		Failed to orbit
ERS-8	06/12/63		Failed to orbit

Table B-1. Scientific and Technology Satellites (Continued)

Spacecraft	Launch Date	Reentry Date	Comments
ERS-9	07/18/63		TRS-4
ERS-10	07/18/63		Failed to separate from Midas-9
ERS-11			No data
ERS-12	10/16/63	07/01/65	TRS-5
ERS-13	07/17/64	07/01/66	TRS-6
ERS-14			No data
ERS-15	08/19/66		ORS-1
ERS-16	06/09/66	03/12/67	ORS-2
ERS-17	07/20/65	07/01/68	ORS-3
ERS-18	04/28/67		
ERS-19			No data
ERS-20	04/28/67		OV5-3
ERS-21	09/26/68		OV5-4
ERS-22			No data
ERS-23			No data
ERS-24			No data
ERS-25			No data
ERS-26			No data
ERS-27	04/28/67		OV5-1
ERS-28	09/26/68	02/15/71	OV5-2
ERS-29	05/23/69		OV5-5
ERS-30	12/13/67	04/28/68	TETR-1
Radose: U.S. Air Force satellites carrying radiation dosimeters			
Radose	06/15/63	07/30/63	
Radose-5E1	09/28/63		SN39
Radose-5E1A	12/05/63		
Radose-5E2	04/21/64		Failed to orbit
Radose-5E3	12/05/63		
Radose-5E4			No data
Radose-5E5	12/12/64		
GGSE: Gravity Gradient Stabilization Experiment conducted by U.S. Navy			
GGSE-1	01/11/64		
GGSE-2	03/09/65		
GGSE-3	03/09/65		
GGSE-4	05/31/67		
GGSE-5	05/31/67		
SERT: Space Electric Rocket Test satellites tested ion-drive engines			
SERT-1	07/20/64		Sub-orbital
SERT-2	02/04/70		
OGO: Orbiting Geophysical Observatory for magneto/atmosphere studies			
OGO-1	09/04/64		
OGO-2	10/14/65	09/17/83	
OGO-3	06/06/66		
OGO-4	07/28/67	08/16/72	
OGO-5	03/04/68		
OGO-6	06/05/69	12/10/79	

Table B-1. Scientific and Technology Satellites (Continued)

Spacecraft	Launch Date	Reentry Date	Comments
OV1: U.S. Air Force multipurpose experiment-carrier satellites			
OV1-1	01/21/65		Failed to orbit
OV1-2	10/05/65		
OV1-3	05/27/65		Failed to orbit
OV1-4	03/30/66		
OV1-5	03/30/66		
OV1-6	11/03/66	12/31/66	
OV1-7	07/13/66		Failed to orbit
OV1-8	07/13/66	01/04/78	
OV1-9	12/11/66		
OV1-10	12/11/66		
OV1-11	07/27/67		
OV1-86	07/27/67	02/22/72	
OV1-12	07/27/67	07/22/80	
OV1-13	04/06/68		
OV1-14	04/06/68		
OV1-15	07/11/68	01/06/68	
OV1-16	07/11/68	08/19/68	Cannonball-1
OV1-17	03/17/69	03/05/70	
OV1-18	03/17/69	08/27/72	
OV1-19	03/17/69		
OV1-20	08/07/71	08/28/71	
OV1-21	08/07/71		
Pegasus: Satellites to study micro-meteroid impact			
Pegasus-1	02/16/65	09/17/78	
Pegasus-2	05/25/65	01/03/79	
Pegasus-3	07/30/65	08/04/69	
OV2: Second generation OV satellites			
OV2-1	10/15/65	07/27/72	Failed to separate from LCS-2
OV2-2			No data
OV2-3	12/21/65	08/17/75	
OV2-4			No data
OV2-5	09/26/68		
OAO: Orbiting Astronomical Observatory: Conducted stellar observations			
OAO-1	04/08/66		
OAO-2	12/07/68		
OAO-B	11/30/70		Failed to orbit
OAO-3	08/21/72		
OV3: Third generation OV satellites			
OV3-1	04/22/66		
OV3-2	10/28/66	09/29/71	
OV3-3	08/04/66		
OV3-4	06/10/66		
OV3-5	01/31/67		
OV3-6	12/04/67	03/09/69	

Table B-1. Scientific and Technology Satellites (Continued)

Spacecraft	Launch Date	Reentry Date	Comments
OV4: Fourth generation OV satellites			
OV4-1R	11/03/66	01/05/67	
OV4-1T	11/03/66	01/11/67	
OV4-2			
OV4-3	11/03/66	01/09/67	Modified Titan II stage
ATS: Application Technology Satellites for geostationary orbit studies			
ATS-1	12/06/66		
ATS-2	04/05/67	02/09/69	Failed to achieve correct orbit
ATS-3	11/05/67		
ATS-4	08/10/68	10/17/68	Failed to achieve correct orbit
ATS-5	08/12/69		
ATS-6	05/30/74		
Biosat: Life science experiments			
Biosat-1	12/14/66	02/15/67	
Biosat-2	09/07/67	09/11/67	
Biosat-3	06/28/69	01/20/70	
OV5: Fifth generation OV satellites			
OV5-1	04/28/67		
OV5-2	09/26/68	02/15/71	
OV5-3	04/28/67		
OV5-4	09/26/68		
OV5-5	05/23/69		
OV5-6	05/23/69		
OV5-7			No data
OV5-8	08/16/68		
OV5-9	05/23/69		
TETR: Test and Traing Satellites			
TETR-1	12/13/67	04/28/68	ERS-30
TETR-2	11/08/68	09/19/79	
TETR-C	08/27/69		Failed to orbit
TETR-4	09/29/71	09/21/81	
Particle and Fields Satellites: Lunar investigations, Apollo-launched			
P&F satellite	08/04/71		
P&F satellite	04/16/72	05/29/72	
HEAO: High Energy Astronomy Observatory			
HEAO-1	08/12/77	03/15/79	
HEAO-2	11/13/78	03/25/82	
HEAO-3	09/20/79	02/07/81	
ISEE: International Sun-Earth Explorer for studying ionosphere			
ISEE-1	10/22/77	0/26/87	IMP-K
ISEE-2	10/22/77	0/26/87	ESA satellite
ISEE-3	08/12/78		ICE

Table B-1. Scientific and Technology Satellites (Continued)

Spacecraft	Launch Date	Reentry Date	Comments
Spartan: Shuttle Pointed Autonomous Research Tool for Astronomy			
Spartan-1	06/20/85	06/24/85	
Spartan Halley	01/28/86		Failed to orbit
Miscellaneous scientific and technology satellites			
Score	12/18/58	01/21/59	
Traac	11/15/61		
ANNA-1A	05/10/62		Failed to orbit
TAVE	09/29/62		
Starad-1	10/26/62	05/10/67	
ANNA-1B	10/31/62		
GRS	06/28/63	02/14/83	
DASH-2	07/18/63	04/12/71	
0.1mÿ Target	08/29/63	09/28/63	
ERSS	06/25/64		
Snapshot	04/03/65		SNAP-10A reactor test
—	04/03/65		
Tempsat-1	08/13/65		
Spasurrod-1	08/13/65		
Porcupine-2	08/13/65		
REP	08/21/65	08/27/65	Ejected by Gemini
Starad-2	09/02/65		Failed to orbit
Bluebell	02/15/66	02/16/66	
Bluebell	02/15/66	02/22/66	
A3	03/18/66	03/23/66	
GGTS	06/16/66		
Pageos	06/23/66		
SGLS	10/12/66	10/21/66	
LOGACS	05/22/67	05/27/67	
—	05/31/67		
—	05/31/67		
Aurora-1	06/29/67		
DATS-1	07/01/67		
Dodge	07/01/67		
Radcat	08/16/68		
Lidos	08/16/68		
RM-18	08/16/68		
UV Radiometer	08/16/68		
Orbis Cal-1	08/16/68		Failed to orbit
Grid Sphere	08/16/68		Failed to orbit
Orbis Cal-2	03/17/69	03/24/69	
PAC-1	08/09/69	04/28/77	
Topo-1	04/08/70		
OFO-1	11/09/70	05/09/71	
RM	11/09/70	02/07/71	
CEP-1	12/11/70		
SESP-1	06/08/71	01/31/82	
Cannonball-2	08/07/71	01/31/72	
Musketball	08/07/71	09/19/71	
Rigid Sphere-2	08/07/71		
Mylar balloon	08/07/71	06/11/72	

Table B-1. Scientific and Technology Satellites (Continued)

Spacecraft	Launch Date	Reentry Date	Comments
Grid Sphere-2	08/07/71	04/14/79	
Grid Sphere-1	08/07/71	01/02/79	
Rigid Sphere-1	08/07/71	09/01/81	
STP	10/17/71		
—	10/02/72		
Sphinx	02/11/74		
SESP 73-5	10/29/74	05/26/75	
GEOS-3	04/09/75		
DAD	12/05/75		
Lageos	05/04/76		
P76-5	05/22/76		
—	06/02/76		
SESP 74-2	07/08/76	04/24/86	
Transat	10/28/77		
IUE	01/26/78		
PIX-1	03/05/78		
HCMM	04/26/78	02/22/81	
Seasat	06/27/78		
Cameo	10/24/78		
Scatha	01/30/79		
SAGE	02/18/79		
Solwind P78-1	02/24/79	09/13/85	
Magsat	10/30/79	06/11/80	
SMM	02/14/80		
DE-1	08/03/81		
DE-2	08/03/81	02/19/83	
SME	10/06/81		
PIX-2	01/26/83		
Hilat-1	06/27/83		
IRT	02/05/84	02/11/84	
LDEF	04/07/84		
AMPTE/CCE	08/16/84		
ERBS	10/05/84		
Geosat	03/13/85		
Nusat-1	04/29/85	02/15/86	
PDP-2	08/01/85	08/01/85	
Glomr	11/01/85	02/26/86	
Oex Target	11/30/85	03/02/87	
ITV-1	12/13/85		
ITV-2	12/13/85	08/09/87	
Polar Bear	11/14/86		
LIPS-3	05/15/87		
Delta Star	03/24/89		
Cobe	11/18/89		
Pacsat	01/22/90		
Webersat	01/22/90		
LACE	02/14/90		
RME	02/14/90		
Pegsat	05/04/90		
Glomar	05/04/90		
POGS/SSR	11/04/90		

Table B-1. Scientific and Technology Satellites (Continued)

Spacecraft	Launch Date	Reentry Date	Comments
TEX	11/04/90		
SCE	11/04/90		
Hubble ST	04/24/90		
Macsat-1	05/09/90		
Macsat-2	05/09/90		
CRRES	07/25/90		

Table B-2. Unmanned Interplanetary and Lunar Spacecraft

Spacecraft	Launch Date	Reentry Date	Comments
Pioneer: Series of lunar/solar/interplanetary probes			
—	08/17/58		Failed to orbit
Pioneer-1	10/11/58	10/12/58	Failed to achieve correct orbit
Pioneer-2	11/08/58		Failed to orbit
Pioneer-3	12/06/58	02/07/58	Failed to achieve correct orbit
Pioneer-4	03/03/59		
—	11/26/59		Failed to orbit
Pioneer-5	03/11/60		
—	09/25/60		Failed to orbit
—	12/15/60		Failed to orbit
Pioneer-6	12/16/65		
Pioneer-7	08/17/66		
Pioneer-8	12/13/67		
Pioneer-9	11/08/68		
Pioneer-E	08/27/69		Failed to orbit
Pioneer-10	03/02/72		
Pioneer-11	04/05/73		
P. Venus-1	05/20/78		
P. Venus-2	08/08/78	02/09/78	
Ranger: Lunar exploration			
Ranger-1	08/23/61	08/30/61	Remained in Earth orbit
Ranger-2	11/18/61	01/20/61	Remained in Earth orbit
Ranger-3	01/26/62		Flew past Moon
Ranger-4	04/23/62	04/26/62	
Ranger-5	10/18/62		Flew past Moon
Ranger-6	01/30/64	02/02/64	
Ranger-7	07/28/64	07/31/64	
Ranger-8	02/17/65	02/20/65	
Ranger-9	03/21/65	03/24/65	
Ranger-10			Cancelled
Ranger-11			Cancelled
Ranger-12			Cancelled
Mariner: Mars, Venus, Mercury flyby			
Mariner-1	07/22/62		Failed to orbit
Mariner-2	08/27/62		
Mariner-3	11/05/64		

Table B-2. Unmanned Interplanetary and Lunar Spacecraft (Continued)

Spacecraft	Launch Date	Reentry Date	Comments
Mariner-4	11/28/64		
Mariner-5	06/14/67		
Mariner-6	02/24/69		
Mariner-7	03/27/69		
Mariner-H	05/08/71		Failed to orbit
Mariner-9	05/30/71		
Mariner-10	11/03/73		
Surveyor: Intended for lunar soft landing and exploration			
Surveyor-1	05/30/66	06/02/66	
Surveyor-2	09/20/66	09/23/66	Impacted on Moon
Surveyor-3	04/17/67	04/20/67	
Surveyor-4	07/14/67	07/17/67	Impacted on Moon
Surveyor-5	09/08/67	09/11/67	
Surveyor-6	11/07/67	01/10/67	
Surveyor-7	01/07/68	01/10/68	
Lunar Orbiter: Photographic mapping of lunar surface			
Lunar Orbiter-1	08/10/66	0/29/66	
Lunar Orbiter-2	11/06/66	0/11/67	
Lunar Orbiter-3	02/04/67	0/ 9/67	
Lunar Orbiter-4	05/04/67	0/ 6/67	
Lunar Orbiter-5	08/01/67	01/31/68	
Viking: Spacecraft consisted of Mars orbiter and Mars landing craft			
Viking Test	02/11/74		Failed to orbit
Viking-1	08/20/75	07/20/76	
Viking-2	09/09/75	09/03/76	
Voyager: Jupiter, Saturn, and outer planets flyby			
Voyager-1	09/05/77		
Voyager-2	08/20/77		
Miscellaneous interplanetary probes			
Magellan	04/05/89		Venus orbiter
Galileo	10/18/89		Jupiter orbiter

Table B-3. Earth Observation Satellites

Spacecraft	Launch Date	Reentry Date	Comments
Tiros: Television and Infrared Observation Satellite (meteorology)			
Tiros-1	04/01/60		
Tiros-2	11/23/60		
Tiros-3	07/12/61		
Tiros-4	02/08/62		
Tiros-5	06/19/62		
Tiros-6	09/18/62		
Tiros-7	06/19/63		
Tiros-8	12/21/63		
Tiros-9	01/22/65		
Tiros-10	07/02/65		
Tiros-M	01/23/70		ITOS-I
Tiros-N	10/13/78		
P35: Military meteorological satellites, followed by RCA Block III			
P35-1	05/23/62		Failed to orbit
P35-2	08/23/62		
P35-3	02/19/63	02/26/79	
P35-4	04/26/63		Failed to orbit
P35-5	09/27/63		Failed to orbit
P35-6	01/19/64		
P35-7	01/19/64		
P35-8	06/17/64		
P35-9	06/17/64		
Nimbus: NASA experimental meteorological satellites			
Nimbus-1	08/28/64	05/16/74	
Nimbus-2	05/15/66		
Nimbus-B	05/18/68		Failed to orbit
Nimbus-3	04/14/69		
Nimbus-4	04/08/70		
Nimbus-5	12/11/72		
Nimbus-6	06/12/75		
Nimbus-7	10/24/78		
P35 (RCA Block 3): Military meteorological satellites			
P35-10	01/18/65	07/13/79	
P35-11	03/18/65		
P35-12	05/20/65		
P35-13	09/09/65		
P35-14	01/06/66		Failed to orbit
P35-15	03/30/66		
ESSA: Environmental Sciences Services Administration, based on Tiros and known as Tiros Operational System (TOS)			
ESSA-1	02/03/66		
ESSA-2	02/28/66		
ESSA-3	10/02/66		
ESSA-4	01/26/67		
ESSA-5	04/20/67		
ESSA-6	11/10/67		

Table B-3. Earth Observation Satellites (Continued)

Spacecraft	Launch Date	Reentry Date	Comments
ESSA-7	08/16/68		
ESSA-8	12/15/68		
ESSA-9	02/26/69		
P35 (RCA Block 4A/4B/5A): Follow-on to RCA Block 3			
P35-16	09/15/66		
P35-17	02/08/67		
P35-18	08/22/67		
P35-19	10/11/67		
P35-20	05/22/68		
P35-21	10/22/68		
P35-22	07/22/69		
P35-23	02/11/70		
P35-24	09/03/70		
P35-25	02/17/71		
NOAA: National Oceanics and Atmospheric Administration satellites based on Tiros-M (NOAA-1, ITOS to NOAA-5) and Tiros-N (NOAA-6 and later)			
NOAA-1	12/11/70		
ITOS-B	10/21/71	07/21/72	Failed to achieve correct orbit
ITOS-C			No data
NOAA-2	10/15/72		
ITOS-E	07/16/73		Failed to orbit
NOAA-3	11/06/73		
NOAA-4	11/15/74		
NOAA-5	07/29/76		
NOAA-6	06/27/79		
NOAA-B	05/29/80	05/03/81	Failed to achieve correct orbit
NOAA-7	06/23/81		
NOAA-8	03/28/83		Not operational
NOAA-9	12/12/84		
NOAA-10	09/17/86		
NOAA-11	09/24/88		
RCA Block 5B/C (DMSP): Defense Meteorological Satellite Program			
RCA BL 5B/C	10/14/71		DMSP-1
RCA BL 5B/C	03/24/72		DMSP-2
RCA BL 5B/C	11/09/72		DMSP-3
RCA BL 5B/C	08/17/73		DMSP-4
RCA BL 5B/C	03/16/74		DMSP-5
RCA BL 5B/C	08/09/74		DMSP-6
RCA BL 5B/C	05/24/75		DMSP-7
RCA BL 5B/C	02/19/76	02/19/76	DMSP-8 Didn't achieve correct orbit
Landsat: Originally Earth Resources Technology Satellite (ERTS)			
Landsat-1	07/23/72		
Landsat-2	01/22/75		
Landsat-3	03/05/78		
Landsat-4	07/16/82		
Landsat-5	03/01/84		

Table B-3. Earth Observation Satellites (Continued)

Spacecraft	Launch Date	Reentry Date	Comments
SMS: Synchronous Meteorological Satellites in geostationary orbit			
SMS-1	05/17/74		
SMS-2	02/06/75		
SMS-C			GOES-1
DMSP F: Improved RCA Block 5D satellites, also Advanced Meteorological Satellite (AMS)			
DMSP F-1	09/11/76		AMS-1
DMSP F-2	06/05/77		
DMSP F-3	05/01/78		
DMSP F-4	07/14/80		
DMSP F	06/06/79		
DMSP F-5	12/21/82		
DMSP F-6	11/18/83		
DMSP F-7	06/20/87		USA-26
DMSP F-8	03/02/88		USA-29
DMSP F-9	01/12/90		USA-68
GOES: Geostationary Operational Environmental Satellite U.S.ed by NOAA			
GOES-1	10/16/75		
GOES-2	06/16/77		
GOES-3	06/16/78		
GOES-4	09/09/80		
GOES-5	05/22/81		
GOES-6	04/28/83		
GOES-G	05/03/86		Failed to orbit
GOES-7	02/26/87		

Table B-4. Communication Satellites

Spacecraft	Launch Date	Reentry Date	Comments
Echo: Aluminized balloons			
Echo A-1	05/13/60		Failed to orbit
Echo-1	08/12/60	05/24/68	
Echo	01/15/62		Failed to orbit
Echo-2	01/25/64	06/07/69	
Courier: First repeater-type communications satellite			
Courier-1A	08/18/60		Failed to orbit
Courier-1B	10/04/60		
Telstar: First commercial communications satellited operated by AT&T			
Telstar-1	07/10/62		
Telstar-2	05/07/63		
Relay:			
Relay-1	12/13/62		
Relay-2	01/21/64		

Table B-4. Communication Satellites (Continued)

Spacecraft	Launch Date	Reentry Date	Comments
Syncom: First geostationary communications satellite			
Syncom-1	02/14/63		Failed to achieve correct orbit
Syncom-2	07/26/63		Failed to achieve correct orbit
Syncom-3	08/19/64		
LES: Lincoln Experimental Satellite sponsored by U.S. Air Force			
LES-1	02/11/65		
LES-2	05/06/65		
LES-3	12/21/65	04/06/68	
LES-4	12/21/65	08/01/77	
LES-5	07/01/67		
LES-6	09/26/68		
LES-7			Cancelled
LES-8	03/15/76		
LES-9	03/15/76		
IDCSP: Initial Defense Communications Satellite Program			
IDCSP-1	06/16/66		
IDCSP-2	06/16/66		
IDCSP-3	06/16/66		
IDCSP-4	06/16/66		
IDCSP-5	06/16/66		
IDCSP-6	06/16/66		
IDCSP-7	06/16/66		
IDCSP	08/26/66		Eight satellites failed to orbit
IDCSP-8	01/18/67		
IDCSP-9	01/18/67		
IDCSP-10	01/18/67		
IDCSP-11	01/18/67		
IDCSP-12	01/18/67		
IDCSP-13	01/18/67		
IDCSP-14	01/18/67		
IDCSP-15	01/18/67		
IDCSP-16	07/01/67		
IDCSP-17	07/01/67		
IDCSP-18	07/01/67		
IDCSP-19	06/13/68		
IDCSP-20	06/13/68		
IDCSP-21	06/13/68		
IDCSP-22	06/13/68		
IDCSP-23	06/13/68		
IDCSP-24	06/13/68		
IDCSP-25	06/13/68		
IDCSP-26	06/13/68		
Tacsat: Experimental military communications satellite			
Tacsat-1	02/09/69		

Table B-4. Communication Satellites (Continued)

Spacecraft	Launch Date	Reentry Date	Comments
SDS: Satellite Data System relay satellite			
SDS-A	03/21/71		
SDS-B	08/21/73		
SDS-1	03/10/75		
SDS-2	06/02/76		
SDS-3	08/06/76		
SDS-4	02/25/78		
SDS-5	08/05/78		
SDS-6	12/13/80		
SDS-7	04/24/81		
SDS-8	07/31/83		
SDS-9	08/28/84		
SDS-10	02/08/85		
SDS-11	02/12/87		
DSCS: Defense Satellite Communications System II			
DSCS II-1	11/03/71		
DSCS II-2	11/03/71		
DSCS II-3	12/13/73		
DSCS II-4	12/13/73		
DSCS II-5	05/20/75	05/26/75	Failed to achieve correct orbit
DSCS II-6	05/20/75	05/26/75	Failed to achieve correct orbit
DSCS II-7	05/12/77		
DSCS II-8	05/12/77		
DSCS II-9	03/25/78		Failed to orbit
DSCS II-10	03/25/78		Failed to orbit
DSCS II-11	12/14/78		
DSCS II-12	12/14/78		
DSCS II-13	11/21/79		
DSCS II-14	11/21/79		
DSCS II-15	10/30/82		
DSCS II-16	10/30/82		DSCS III-1
Westar: Owned by Western Union Telegraph			
Westar-1	04/13/74		
Westar-2	10/10/74		
Westar-3	08/10/79		
Westar-4	02/26/82		
Westar-5	06/09/82		
Westar-6	02/03/84	01/16/84	Failed to achieve correct orbit
RCA Satcom: Owned by RCA Communications			
RCA Satcom-1	12/13/75		
RCA Satcom-2	03/26/76		
RCA Satcom-3	12/07/79		Failed to achieve correct orbit
RCA Satcom-3R	11/20/81		
RCA Satcom-4	01/16/82		
RCA Satcom-5	10/20/82		
RCA Satcom-6	04/11/83		
RCA Satcom-7	09/08/83		

Table B-4. Communication Satellites (Continued)

Spacecraft	Launch Date	Reentry Date	Comments
Comstar: Owned by Comsat General			
Comstar-1	05/13/76		
Comstar-2	07/22/76		
Comstar-3	06/29/78		
Comstar-4	02/21/81		
FLTSATCOM: Owned by the U.S. Navy			
FLTSATCOM-1	02/09/78		
FLTSATCOM-2	05/04/79		
FLTSATCOM-3	01/18/80		
FLTSATCOM-4	10/31/80		
FLTSATCOM-5	08/06/81		
FLTSATCOM-6	03/26/87		Failed to orbit
FLTSATCOM-7	12/05/86		
FLTSATCOM-8	09/25/89		
SBS: Satellite Business System, owned by Comsat General			
SBS-1	11/15/80		
SBS-2	09/24/81		
SBS-3	11/11/82		
SBS-4	08/31/84		
SBS-5	09/08/88		
SBS-6	10/12/90		
DSCS: Defense Satellite Communications System III			
DSCS III-1	10/30/82		DSCS II-1
DSCS III-2	01/31/84		
DSCS III-3	10/03/85		
DSCS III-4	10/03/85		
DSCS III-5	04/09/89		
DSCS III-6	04/09/89		
Galaxy: Owned by Hughes Communications			
Galaxy-1	06/28/83		
Galaxy-2	09/22/83		
Galaxy-3	09/21/84		
Galaxy-4			
Galaxy-5			
Galaxy-6	10/12/90		
TDRS: Tracking and Data Relay System owned by NASA			
TDRS-1	04/05/83		
TDRS-B	01/28/86		Failed to orbit
TDRS-3	09/29/88		
TDRS-4	03/13/89		
Telstar: Owned by AT&T			
Telstar 3-A	07/28/83		
Telstar 3-B			
Telstar 3-C	09/01/84		
Telstar 3-D	06/19/85		

Table B-4. Communication Satellites (Continued)

Spacecraft	Launch Date	Reentry Date	Comments
Spacenet: Owned by Southern Pacific Communications			
Spacenet-1	05/23/84		
Spacenet-2	11/10/84		
Spacenet-3	09/12/85		Failed to orbit
Spacenet-3R	03/11/88		
Syncom IV: Military communications satellite, also Leasat			
Syncom IV-1	11/10/84		
Syncom IV-2	08/31/84		
Syncom IV-3	04/13/85		
Syncom IV-4	08/29/85		Failed to achieve correct orbit
Syncom IV-5	01/09/90		
G Star: Owned by General Telephone and Electronics			
G Star-1	05/08/85		
G Star-2	03/28/86		
G Star-3	09/08/88		Failed to achieve correct orbit
G Star-4	11/20/90		
ASC: American Satellite Corporation			
ASC-1	08/27/85		
Satcom K: Owned by GE Americon Communications, also RCA Americom			
Satcom K-1	01/12/86		RCA Americom-1
Satcom K-2	11/28/85		RCA Americom-2
Panamsat: Owned by Pan American Satellite Corporation			
Panamsat	06/15/88		
Satcom K: Owned by GE Americon Communications			
Satcom C-1	11/20/90		

Table B-5. Navigation Satellites

Spacecraft	Launch Date	Reentry Date	Comments
Transit: First series of U.S. Navy navigational satellites			
Transit-1	09/17/59		Failed to orbit
Transit-1B	04/13/60	05/10/57	
Transit-2A	06/22/60		
Transit-3A	11/30/60		Failed to orbit
Transit-3B	02/21/61	03/30/61	Failed to achieve correct orbit
Transit-4A	06/29/61		
Transit-4B	11/15/61		
Transit-5A1	12/19/62	09/25/86	
Transit-5A2	04/05/63		Failed to orbit
Transit-5A3	06/16/63		
Transit-5BN1	09/28/63		
Transit-5BN2	12/05/63		
Transit-5BN3	04/21/64		Failed to orbit
Transit-5C1	06/03/64		

Table B-5. Navigation Satellites (Continued)

Spacecraft	Launch Date	Reentry Date	Comments
Secor: Sequential Collection of Range satellites operated by U.S. Army for location surveys			
Secor-1A	01/24/62		Failed to orbit
Secor-1	01/11/64		
Secor-2	03/11/65	02/26/68	
Secor-3	03/09/65		
Secor-4	04/03/65		
Secor-5	08/10/65		
Secor-6	06/09/66	07/06/67	
Secor-7	08/19/66		
Secor-8	10/05/66		
Secor-9	06/29/67		
Secor-10	05/18/68		Failed to orbit
Secor-11	08/16/68		Failed to orbit
Secor-12	08/16/68		Failed to orbit
Secor-13	04/14/69		
NNSS: Navy Navigational Satellite System, also called Transit O and Oscar			
NNSS-30010	10/06/64		
NNSS-30020	12/12/64		
NNSS-30030	03/11/65	06/14/65	
NNSS-30040	06/24/65		
NNSS-30050	08/13/65		
NNSS-30060	12/21/65		
NNSS-30070	01/28/66		
NNSS-30080	03/25/66		
NNSS-30090	05/19/66		
NNSS-30100	08/17/66		
NNSS-30110			Used as Transat
NNSS-30120	04/13/67		
NNSS-30130	05/18/67		
NNSS-30140	09/25/67		
NNSS-30150			In storage
NNSS-30160			Used as Hilsat
NNSS-30170			Used as Polar Bear
NNSS-30180	03/01/68		
NNSS-30190	08/27/70		
NNSS-30200	10/30/73		
NNSS-30210			In storage
NNSS-30220			In storage
NNSS-30230			
NNSS-30240	08/03/85		
NNSS-30250			
NNSS-30260			In storage
NNSS-30270	09/16/87		
NNSS-30280			In storage
NNSS-30290	09/16/87		
NNSS-30300	08/03/85		
NNSS-30310	08/25/88		
NNSS-30320	04/26/88		

Table B-5. Navigation Satellites (Continued)

Spacecraft	Launch Date	Reentry Date	Comments
Timation: Also Navigation Technology Satellite (NTS) owned by U.S. Navy			
Timation-1	05/31/67		
Timation-2	09/30/69	09/30/70	
Timation-3	07/14/74		NTS-1
NTS-2	06/23/77		
NTS-3	09/06/89		
TIP: Transit Improvement Program owned by the U.S. Navy			
TIP-1	09/02/72		Triad
TIP-2	10/12/75		
TIP-3	09/01/76	05/30/81	
Navstar: U.S. Navy operational navigational satellites, also Global Positioning System (GPS) and Navigation Development Satellite (NDS)			
Navstar-1	02/22/78		
Navstar-2	05/13/78		
Navstar-3	10/07/78		
Navstar-4	12/11/78		
Navstar-5	02/09/80		
Navstar-6	04/26/80		
Navstar-7	12/18/81		Failed to orbit
Navstar-8	07/14/83		
Navstar-9	06/13/84		
Navstar-10	09/08/84		
Navstar-11	10/09/85		
Nova: U.S. Navy navigational satellites			
Nova-1	05/15/81		NNSS 30480
Nova-2	10/11/84		NNSS 30490
Nova-3	06/16/88		NNSS 30450

Table B-6. Miscellaneous Military Satellites

Spacecraft	Launch Date	Reentry Date	Comments
Surcal: Surveillance Calibration owned by the U.S. Navy			
Surcal-1A	01/24/62		Failed to orbit
Surcal-1B	12/12/62	01/18/66	
Surcal-1C	06/15/63	07/05/63	
Surcal-2	12/12/62	02/05/67	
Surcal	03/09/65	03/27/81	
Surcal	03/09/65		Dodecapol-1
Surcal	08/13/65		Two satellites not separated
Surcal	08/13/65		Dodecap. ' 2
Surcal	08/13/65		
Surcal	08/13/65		
Surcal	08/13/65		
Surcal	05/31/67		
Surcal	05/31/67		
Surcal	05/31/67		
Calsphere: U.S. Air Force radar calibration satellites			
Calsphere-1	12/12/62	07/01/63	
Calsphere-2	10/06/64		
Calsphere-3	10/06/64		
Calsphere-4	08/13/65		
Calsphere-5	02/17/71		
Calsphere-6	02/17/71		
Calsphere-7	02/17/71		
Hitchiker: Secondary payloads carried on military launches			
Hitchiker-1	03/18/63		Failed to orbit
Hitchiker-2	06/26/63		
Hitchiker-3	10/29/63	05/23/65	
Hitchiker-4	12/21/63	01/07/64	
Hitchiker-5	07/06/64	01/03/65	
Hitchiker-6	08/14/64	03/08/79	P-11
Hitchiker-7	10/23/64	02/23/65	
Hitchiker-8	04/28/65	10/31/69	
Hitchiker-9	06/25/65	08/22/68	
Hitchiker-10	08/03/65	06/17/68	
Hitchiker-11	05/14/66	10/27/70	
Hitchiker-12	08/16/66	03/05/70	
Hitchiker-13	09/16/66	05/09/68	
Hitchiker-14	05/09/67		
Hitchiker-15	06/16/67	10/22/68	
Hitchiker-16	11/02/67	03/28/69	
Hitchiker-17	01/24/68	03/04/70	
Hitchiker-18	03/14/68	01/03/70	
Hitchiker-19	06/20/68	01/11/70	
Hitchiker-20	09/18/68	09/28/69	
Hitchiker-21	12/12/68		
Hitchiker-22	02/05/69		
Hitchiker-23	03/19/69	02/06/71	
Hitchiker-24	05/01/69	02/16/70	
Hitchiker-25	09/22/69	05/16/71	

Table B-6. Miscellaneous Military Satellites (Continued)

Spacecraft	Launch Date	Reentry Date	Comments
Hitchiker-26	03/04/70	01/10/71	
Hitchiker-27	05/20/70	03/08/74	
Hitchiker-28	11/18/70	09/14/77	
Hitchiker-29	09/10/71	02/03/76	
Hitchiker-30	01/20/72	01/23/72	
Hitchiker-31	07/07/72	05/06/78	
Hitchiker-32	10/10/72		
Hitchiker-33	11/10/73	02/26/78	
Hitchiker-34	11/10/73	01/13/73	
Hitchiker-35	04/10/74		
Hitchiker-36	04/10/74	02/22/80	
Hitchiker-37	10/29/74	01/23/80	
Hitchiker-38	12/04/75	05/01/78	
Hitchiker-39	07/08/76	04/24/86	
Hitchiker-40	03/16/78		
Hitchiker-41	03/16/79		
Hitchiker-42	05/11/82		
Pickaback: Secondary payloads carried on military launches			
Pickaback	10/25/63	10/28/63	
Pickaback	10/23/64	10/29/64	
Pickaback	11/08/65	01/11/65	
Pickaback	01/19/66	01/23/66	
Pickaback	06/03/66	06/09/66	
Pickaback	11/02/66	01/16/66	
Lincoln Calibration Sphere: Experimental U.S.AF calibration satellite			
LCS-1	05/06/65		
LCS-2	10/15/65	07/27/72	
LCS-3	08/16/68		Failed to orbit
LCS-4	08/07/71	09/01/81	Rigid Sphere-1

Source: Heyman, J. *Spacecraft Tables, 1957-1990*, San Diego, CA: Univelt, Inc., 1991.

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ABBREVIATIONS

ABBREVIATIONS

For some of the abbreviations, the program to which the abbreviation applies is indicated in parentheses.

A&R	Automation and Robotics (SEI)
AACS	Attitude and Articulation Control Subsystem (Voyager)
AAP	Apollo Applications Program
AAPO	Apollo Applications Program Office
AAS	American Astronautical Society
ABMA	Army Ballistic Missile Agency (Mercury Project)
ACERV	Assured Crew Emergency Return Vehicle (SSF)
ACR	Active Cavity Radiometer
ACRIM	Active Cavity Radiometer Irradiance Monitor (EOS)
ACRIM2	Active Cavity Radiometer Irradiance Monitor (UARS)
ACRV	Assured Crew Return Vehicle (SSF)
ACTS	Advanced Communications Technology Satellite
ADEOS	Advanced Earth Observing Satellite (Japan)
AEIP	Augmented Engine Improvement Program (Titan Program)
AES	Apollo Extension Program
AFSLV	Air Force Small Launch Vehicle (Pegasus, OSC)
AGE	Aerospace Ground Equipment
AIA	Aerospace Industries Association
AIM	Astrometric Interferometry Mission
AIRS	Atmospheric IR Sounder (EOS)
ALDP	Advanced Launch Development Program (NLS)
ALEXIS	Array of Low-Energy X-ray Imaging Sensors
ALS	Advanced Launch System
AM	Airlock Module (Skylab)
AM/MDA	Airlock Module/Multiple Docking Adapter (Skylab)
AMPTE	Advanced Magnetospheric Particle Tracer Experiment
AMR	Atlantic Missile Range

AMROC	American Rocket Company
AMS	Apogee and Maneuvering Stage
AMSSA	Assured Mission Support Space Architecture
AMSU	Advanced Microwave Sounding Units (NOAA satellite, EOS)
AOSO	Advanced Orbiting Solar Observatory
APEX	Advanced Photovoltaic and Electronics Experiment (USAF)
APT	Automatic Picture Transmission TV (Tiros, NOAA satellite, ITOS, Nimbus, ESSA)
ARACOR	Advanced Research and Applications Corporation
ARC	Ames Research Center
ARDC	Air Research and Development Center
ARTEMIS	Africa Real Time Environmental Monitoring Using Imaging Satellites
ASCM	Advanced Spaceborne Computer Module
ASCS	Attitude Stabilization and Control System
ASPO	Apollo Spacecraft Program Office
ASRM	Advanced Solid Rocket Motor (STS)
ASSP	Architecture for Survivable Systems Processing (Honeywell, SDIO)
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer (EOS)
ASTP	Advanced Satellite Technology Program
ATAC	Advanced Technology Advisory Committee
ATD	Advanced Turbopump Development (STS, SSME)
ATF	Astrometric Telescope Facility
ATLAS-1	Atmospheric Laboratory for Applications and Sciences-1 (formerly the Earth Observation Mission-1 (EOM-1))
ATM	Apollo Telescope Mount
ATMOS	Atmospheric Trace Molecules Observed by Spectroscopy
AVCS	Advanced Vidicon Camera System (Nimbus, ITOS, NOAA satellite, ESSA)
AVHRR	Advanced Very High Resolution Radiometer (NOAA satellite, TIROS)
AWS	Advanced Warning System
AXAF	Advanced X-ray Astronomy Facility
BATSE	Burst and Transient Source Experiment (GRO)
BECO	Booster Engine Cut Off
BJ	Big Joe (Mercury Program)
BRL	Ballistics Research Laboratory
BSTS	Boost Surveillance and Track System

BUV	Backscattered Ultraviolet (Nimbus)
CCDS	Center for the Commercial Development of Space
CCS	Command Control Subsystem (Voyager)
CCZ	Command and Control Zone (SSF)
CDCF	Cosmic Dust Collector Facility
CDD	Cosmic Dust Detector (Mariner)
CDOS	Customer Data and Operations System
CDR	Critical Design Review
CELV	Complementary Expendable Launch Vehicle
CEP	Cylindrical Electrostatic Probe (Nimbus)
CERES	Cloud and Earth Radiant Energy System (EOS)
CETA	Crew Equipment Translation Aid (SSF)
CFW	Certification of Flight-worthiness
CI	Configuration Inspection
CLAES	Cryogenic Limb Array Etalion Spectrometer (UARS)
CLAWS	Coherent Launch-site Atmospheric Wind Sounder (KSC)
CM	Command Module (Apollo Program)
COBE	Cosmic Background Explorer
COCOM	Coordinating Committee on Multilateral Export Controls
CODMAC	Committee on Data Management and Computation
COMET	Commercial Experiment Transporter
COMPTEL	Imaging Compton Telescope (GRO)
COMSAT	Communications Satellite Corporation
COMSTAC	Commercial Space Transportation Advisory Committee
COSPAS/SARSAT	A search and rescue satellite system launched and operated jointly by the Soviet Union (COSPAS) and the United States, France and Canada (SARSAT). Norway, Britain, Bulgaria, Finland, and Denmark and others also participate in the program.
COSTAR	Corrective Optics Space Telescope Axial Replacement (HST)
CPT	Charged Particle Telescope (Mariner)
CRAF	Comet Rendezvous-Asteroid Flyby
CREDA	Cooperative Research and Development Agreement
CRNE	Cosmic Ray Nuclei Experiment
CRO	Chemical Release Observation Experiment
CRRES	Combined Release and Radiation Effects Satellite
CRT	Cosmic Ray Telescope (Mariner)
CSAT	Combined Systems Acceptance Test (Gemini Program)

CSM	Command and Service Module
CSTC	Consolidated Space Test Center (Onizuka AFS, CA)
CZCS	Coastal Zone Color Scanner (Nimbus)
DCR	Design Certification Review
DCS	Data Collection System (SMS, GOES)
DCWS	Debris Collision Warning System
DDAU	Digital Data Acquisition Unit
DDPS	Digital Data Processing System
DMSP	Defense Meteorological Satellite Program
DSCS	Defense Satellite Communication System
DSN	Deep Space Network
DSV	Douglas Space Vehicle
DTS	Delta Transfer System
EDO	Extended Duration Orbiter (STS, SSF)
EGRET	Energetic Gamma Ray Experiment (GRO)
ELV	Expendable Launch Vehicle
EOM	Earth Observation Mission
EOS	Earth Observing System (contemporary), Earth Observation Satellite
EOSAT	Earth Observing Satellite Company
EOS SAR	EOS Synthetic Aperture Radar (EOS)
EOSDIS	Earth Observing System's Data and Information System
EOSP	Earth Observation Scanning Polarimeter (EOS)
EPD	Energetic Particle Detector (Galileo)
ER	Electron Reflectometer (Mars Observer)
ERB(E)	Earth Radiation Budget (Experiment) (Landsat, NOAA satellite, Nimbus)
EREP	Earth Resources Experiments Package
EROS	Earth Resources Observation System
ERS	European Remote Sensing Satellite
ERTS	Earth Resources Technology Satellite
ESSA	Environmental Science Services Administration
ESA	European Space Agency
ET	External Tank (STS)
ETM	Enhanced Thematic Mapper (Landsat)
ETR	Eastern Test Range
EUVE	Extreme Ultraviolet Explorer

EUVS	Extreme Ultraviolet Spectrometer (Galileo)
FDS	Flight Data Subsystem
FEWS	Follow-on Early Warning System
FGS	Free Guidance Sensors (HST)
FOC	Faint-Object Camera (HST)
FPR	Flat Plate Radiometer (ESSA, ITOS, NOAA satellite)
FOS	Faint-Object Spectrograph (HST)
F-Sat	Lockheed "frugal" satellite bus program
FWS	Filter Wedge Spectrometer (Nimbus)
GFY	Government Fiscal Year
GGI	GPS Geoscience Instrument (EOS)
GGS	Global Geospace Science
GISS	Goddard Institute for Space Studies
GLRS	Geoscience Laser Ranging System (EOS)
GOES	Geostationary Operational Environmental Satellite
GMS	Geostationary Meteorological Satellite
GOS	Geomagnetic Observing System (EOS)
GPO	Gemini Program Office
GRM	Geopotential Research Mission
GRO	Gamma Ray Observatory
GRS	Gamma Ray Spectrometer (Mars Observer)
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
GTO	Geosynchronous Transfer Orbit
HAINS	High Accuracy Inertial Navigation Subsystem (STS)
HALOE	Halogen Occultation Experiment (UARS)
HB(E)	Heat Budget (Experiment) (TIROS)
HCMR	Heat Capacity Mapping Radiometer (HCMM satellite)
HEAO	High Energy Astronomy Observatory
HEAT	Hybrid Engine Analysis and Technology
HESP	High Efficiency Solar Panel
HETS	High Energy Telescope Subsystem (Voyager)
HFM	High-Field Magnetometer (Voyager)
HHMU	Hand-Held Maneuvering Unit
HIC	High Energy Ion Counter (Galileo)
HIRDLS	High Resolution Dynamics Limb Sounder (EOS)

HIRIS	High-Resolution Imaging Spectrometer (EOS)
HIRS	High Resolution Temperature Sounder (Nimbus)
HLLV	Heavy Lift Launch Vehicle (NLS)
HL-20	Lockheed Corporation designation for PLS development system
HRDI	High Resolution Doppler Imager (UARS)
HRIR	High Resolution Infrared Radiometer (Nimbus)
HRIS	High Resolution Infrared Sounder (Nimbus)
HRSO	High Resolution Solar Observatory
HSC	Houston Space Center
HSCT	High speed Civil Transport
HSP	High-Speed Photometer (HST)
HST	Hubble Space Telescope
HST-OTA	Hubble Space Telescope-Optical Telescope Assembly
HST-SSM	Hubble Space Telescope-Support Systems Module
IABS	Integrated Apogee Boost System (GE Astro Space)
IAF	International Astronautical Federation
IBSS	Infrared Background Signature Survey Satellite (SDIO)
ICE	See ISEE
ICBP	International Geosphere-Biosphere Program
IDCS	Image Dissector Camera System (Nimbus)
INMARSAT	International Maritime Satellite Organization
IPEI	Ionospheric Plasma and Electrodynamics Instrument (EOS)
IPS	Instrument Pointing System (STS/Spacelab)
IRAS	Infrared Astronomy Satellite
IRIS	Infrared Interferometer Spectrometer (Nimbus, Mariner, Voyager)
IRLS	Interrogation Recording and Location Subsystem (Nimbus)
IRR	Infrared Radiometer (Mariner)
IRS	Infrared Spectrometer (Mariner)
IRTM	Infrared Thermal Mapper (Voyager)
ISAMS	Improved Stratosphere and Mesopheric Sounder (UARS)
ISEE	International Sun Earth Explorer
ISSO	International Small Satellite Organization
ISTP	International Solar-Terrestrial Physics Program
ITIP	Improved Transtage Injector Program
ITP	Integrated Technology Program
ITOS	Improved Tiros Observation Satellite

ITPR	Infrared Temperature Profile Radiometer (Nimbus)
IU	Instrument Unit (Skylab)
IUE	International Ultraviolet Explorer
IUS	Inertial Upper Stage (STS), Interim Upper Stage (STS, earlier name)
IVV	Independent Verification and Validation
JERS	Japan Earth Resources Satellite
JSC	Johnson Space Center
JPL	Jet Propulsion Laboratory
JUSCISP	Japan-U.S. Cooperation in Space Project
KSC	Kennedy Space Center
LACE	Low-power Atmospheric Compensation Experiment
LAM	Liquid Apogee Motor
LAGEOS	Laser Geodynamic Satellite
LandWiFS	Land Wide Field Sensor
LAWS	Laser Atmospheric Wind Sounder (EOS)
LaRC	Langley Research Center
LBNP	Lower Body Negative Pressure (STS)
LC	Launch Complex
LDEF	Long Duration Exposure Facility
LeRC	Lewis Research Center
LEM	Lunar Excursion Module (Apollo Program)
LEMPA	Low Energy Magnetospheric Particle Analyzer (Voyager)
LEO	Low Earth Orbit, Large Earth Orbit (Gemini Program), Lunar Exploration Office
LEPT	Low Energy Particle Telescope (Voyager)
LETS	Low Energy Telescope Subsystem (Voyager)
LFM	Low Field Magnetometer
LIDAR	Light Intensity Detection and Ranging
LIMS	Limb Infrared Monitoring (of the Atmosphere) (Nimbus)
LIS	Lightning Imaging Sensor (EOS)
LJ	Little Joe (Mercury Program)
LRIR	Limb Radiance Infrared Radiometer (Nimbus)
LTTAID	Long Tank Thrust Augmented Improved Thor Delta
MA	Mercury Atlas
MACSAT	Multiple Access Communication Satellite

MAPS	Measurement of Air Pollution from Space, Measurement of Air Pollution from Satellites (STS/Spacelab); Modular Antenna Pointing System
MARSNET	ESA counterpart to MESUR
MASTIF	Multiple Axis Space Test Inertial Facility (Mercury Program)
MAWD	Mars Atmospheric Water Detector (Voyager)
MCC	Mission Control Center
MDA	Multiple Docking Adapter (Skylab)
MESUR	Mars Environmental Survey (SEI)
METEOSAT	European Meteorological Satellite
MHS	Microwave Humidity Sounder (EOS)
MILA	Merritt Island Launch Area
MILSATCOM	Military Satellite Communication
MIMR	Multifrequency Imaging Microwave Radiometer (EOS)
MISR	Multi-angle Imaging Spectro-Radiometer (EOS)
MLLV	Multipurpose Large Launch Vehicle
MLS	Microwave Limb Sounder (UARS, EOS)
MLV	Medium Launch Vehicle
MMH	Monomethyl Hydrazine (propellant)
MMS	Multimission Modular Spacecraft (SSF)
MO&DA	Mission Operations and Data Analysis (Cost/funding category)
MOC	Mars Observer Camera
MODIS-N/T	Moderate Resolution Imaging Spectrometer-Nadir/Tilting (EOS)
MODM	Manned One Day Mission (Mercury Program)
MOL	Manned Orbiting Laboratory
MOLA	Mars Observer Laser Altimeter
MOPITT	Measurements of Pollution in the Troposphere (EOS)
MORL	Manned Orbiting Research Laboratory
MPE	Mission to Planet Earth
MPLM	Mini Pressurized Logistics Modules (SSF)
MR	Mercury Redstone
MR-BD	Mercury Redstone-Booster Development
MRIR	Medium Resolution Infrared Radiometer (Nimbus)
MRS	Mobile Remote Servicer (SSF)
MSC	Manned Spacecraft Center (later JSC)
MSFC	Marshall Space Flight Center
MSS	Multi-Spectral Scanner (Landsat), Mobile Servicing System (SSF)

MSX	Mid-course Space Experiment (SDIO)
MTC	Man Tended Capability (SSF)
MUSE	Monitor of Ultraviolet Solar Energy (Nimbus)
NACA	National Advisory Committee for Aeronautics
NAFIS	NASA Accounting and Financial Information Management System
NASA	National Aeronautics and Space Administration
NASCOM	NASA Communications Network
NASP	National Aerospace Plane (X-30)
NCAR	National Center for Atmospheric Research
NEMS	Nimbus E Microwave Spectrometer
NESDIS	National Environmental Satellite, Data, and Information Service
NIMS	Near Infrared Mapper Spectrometer (Galileo)
NLS	National Launch System
NOAA	National Oceanic and Atmospheric Administration, Tiros satellite designation
NPO	National Program Office
NRL	National Research Laboratory
NROSS	Navy Remote Ocean Sensing System
NROSS/NSCAT	Navy Remote Ocean Sensing Survey Satellite/NASA Scatterometer
NSC	National Space Council
NSSDC	National Space Science Data Center
NTO	Nitrogen Tetroxide
NTR	Nuclear Thermal Rocket
OAET	Office of Aeronautics, Exploration and Technology (OAST predecessor, NASA)
OAMS	Orbital Attitude and Maneuvering System (Gemini Program)
OAO	Orbiting Astronomical Observatory
OART	Office of Advanced Research and Technology
OAST	Office of Aeronautics and Space Technology (OAET successor, NASA)
OCE	Ocean Color Experiment (STS/Spacelab)
OCP	Office of Commercial Programs (NASA)
OCST	Office of Commercial Space Transportation
OGO	Orbiting Geophysical Observatory
OMS	Orbital Maneuvering System (STS)
OMSF	Office of Manned Space Flight
OMV	Orbital Maneuvering Vehicle

ORU	Orbital Replacement Unit
OSC	Orbital Sciences Corporation
OSF	Office of Space Flight
OSL	Orbiting Solar Laboratory
OSO	Orbiting Solar Observatory
OSSA	Office of Space Science and Applications
OSSE	Oriented Scintillation Spectrometer Experiment (GRO)
OTDA	Office of Tracking and Data Acquisition
OTV	Orbital Transfer Vehicle
OWS	Orbital Workshop (Skylab)
PAC	Packaged Attitude Control system
PAD	Program Approval Document
PAM	Payload Assist Module (Delta, SSUS variant for STS)
PARD	Pilotless Aircraft Research Division
PCM	Pulse Code Modulation
PDA	Predelivery Acceptance Tests (Gemini Program)
PDRD	Program Definition and Requirements Document
PEM	Particle Experiment Monitor (UARS)
PICS	Positive Ion Composition Spectrometer (Nimbus)
PIRC	Policy Implementation Review Committee (National Space Council)
PL	Payload
PLS	Personnel Launch System
PMC	Permanently Manned Capability (SSF)
PMIRR	Pressure Modulator Infrared Radiometer (Mars Observer)
PMR	Pressure Modulated Radiometer (Nimbus)
POOMSCOB	Polar Orbiting Operational Meteorological Satellite Coordination Board
POS	Proximity Operations Stage (SSF)
PPR	Photopolarimeter Radiometer (Galileo)
PRR	Preliminary Requirements Review
PSR	Precision Segmented Reflection
R&PM	Research and Program Management
R&T	Research and Technology
RAIDS	Remote Atmospheric and Ionospheric Detection System (NOAA satellite)
R&PM	Research and Program Management
R&T	Research and Technology

RBV	Return Beam Vidicon (Landsat)
RCS	Reaction Control System (STS)
RDR	Redesigned Rocket Motor (STS)
REX	Radiation Experiment
ROSAT	Roentgen Satellite
RPM	Radiation and Particle Measurement (Experiment) (Nimbus)
RTAC	Research and Technology Advisory Council
RTG	Radioisotope Thermoelectric Generator (spacecraft electric power)
RTR	Real Time Radiographic
RTTC	Regional Technology Transfer Center
SAFIRE	Spectroscopy of the Atmosphere using Far Infrared Emission (EOS)
SAGA	Solar Array Gain Augmentation (software, HST)
SAGE III	Stratosopheric Aerosol and Gas Experiment III (EOS)
SAM II	Stratospheric Aerosol Measurement (Nimbus)
SAMPEX	Solar, Anomalous and Magnetospheric Particle Explorer
SAMS	Stratospheric and Mesospheric Sounder (Nimbus)
SAO	Smithsonian Astrophysical Observatory
SAR	Synthetic Aperture Radar (Seasat)
SARSAT	See COSPAS/SARSAT
SBUV	Solar Backscatter Ultraviolet (/TOMS, Nimbus)
SBUV/2	Solar Backscatter Ultraviolet Spectral Radiometer (NOAA satellite)
SBWAS	Space-Based Wide Area Surveillance
SCAMS	Scanning Microwave Sounder (Nimbus)
SCMR	Surface Composition Mapping Radiometer (Nimbus)
SCOTS	Shuttle Compatible Orbital Transfer System
SCR	Selective Chopper Radiometer (Nimbus)
SEALAR	Sea-Launch and Recovery (USN booster technology program)
SEASAT	Ocean Sensing Satellite
SeaWiFS	Sea Wide Field Sensor
SEI	Space Exploration Initiative
SEB	Source Evaluation Board
SEM	Space Environment Monitor (SMS, GOES, NOAA satellite)
SEOTV	Solar Electric Orbital Transfer Vehicle
SERDP	Strategic Environmental Research and Development Program
SESL	Space Environmental Simulation Laboratory
SETI	Search for Extraterrestrial Intelligence

SHEAL	Shuttle High Energy Astrophysics Laboratory
SIR	Shuttle Imaging Radar
SIRS	Satellite Infrared Spectrometer (Nimbus)
SIRTF	Space Infrared Telescope Facility
SISEX	Spaceborne Imaging Spectrometer Equipment
SL	Skylab
SLA	Spacecraft Lunar Module Adapter
SLCSAT	Submarine Laser Communication Satellite (USN)
SLS	Spacelab Life Sciences
SLV	Space Launch Vehicle, Soft Landing Vehicle, Satellite Launching Vehicle, Saturn Launch Vehicle
SM	Service Module (Apollo Program)
SME	Solar Mesopheric Explorer
SMEAT	Skylab Medical Experiments Altitude Test
SMIRR	Shuttle Multispectral Infrared Radiometer (STS/Spacelab)
SMMR	Scanning Micr[illegible] Multispectral Radiometer (Seasat, Nimbus)
SMS	Synchronous Meteorological Satellite
SNAP	System for Nuc[illegible]ear Auxillary Power
SOFIA	Stratospheric Observatory for Far-Infrared (747-based)
SOHO	Solar and Heliographic Observatory
SOLSTICE	Solar Stellar Irradiance Comparison Experiment (UARS; -II, EOS)
SPADVOS	Spaceborne Direct View Optical System
SPAS	Shuttle Pallet Satellite II
SPDM	Special Purpose Dextrous Manipulator
SPM	Solar Proton Monitor (NOAA satellite, GOES)
SPP	Solar Plasma Probe (Mariner)
SR	Scanning Radiometer (ITOS, NOAA satellite)
SR&QA	Safety, Reliability and Quality Assurance
SRB	Solid Rocket Booster
SRM	Solid Rocket Motor (STS)
SRMU	Solid Rocket Motor Upgrade (Titan)
SMS	Synchronous Meteorological Satellite (GOES precursor)
SSEIC	Space Station Engineering and Integration Contractor (SSF)
SSES	Solar System Exploration Subcommittee (NASA)
SSESM	Spent-Stage Experimental Module
SSF	Space Station Freedom

SSME	Space Shuttle Main Engine (STS)
SSRM	Space Station Remote Manipulator
SSTAC	Space Systems and Technology Advisory Committee (NASA)
SSTO	Single Stage to Orbit
SSUS-A/-D	Spinning Solid Upper Stage-Atlas/-Delta (STS, PAM variant for Delta)
STAR1	Satellite Tracking and Recording System (Landsat)
STBE	Space Transportation Booster Engi[illegible] [illegible]TS)
STDN	Spaceflight Tracking and Data Network
STG	Space Task Group (Mercury Program, STS)
STIKSCAT	Stick Scatterometer (EOS)
STL	Space Technology Laboratory
STLV	Slow-Turning Lateral Vessel (STS/SSF life sciences research)
STME	Space Transportation Main Engine
STS	Space Transportation System
SUSIM	Solar Ultraviolet Spectral Irradiance Monitor (UARS)
SWIRLS	Stratospheric Wind Infrared Limb Sounder (EOS)
T&DR	Tracking and Data Relay (Nimbus)
TAID	Thrust Augmented Improved Thor Delta
TAT	Thrust Augmented Thor (Agena)
TATD	Thrust Augmented Thor Delta
TDRSS	Tracking and Data Relay Satellite System
TES	Tropospheric Emission Spectrometer (EOS), Thermal Emission Spectrometer (Mars Observer)
TET	The Electron Telescope (Voyager)
THIR	Temperature Humidity Infrared Radiometer (Nimbus)
TIROS	Television Infrared Observation Satellite
TLV	Target Launch Vehicle (Gemini Program)
TM	Thermatic Mapper (Landsat)
TOGA	Tropical Oceans-Global Atmosphere Program
TOMS	Total Ozone Mapping Spectrometer (Nimbus), Total Ozone Monitoring System (Nimbus)
TOPEX	Topography [illegible] for Ocean [illegible]
TOPSAR	Topographic [illegible]
TOS	Transfer Orbit Stage
[illegible]TS	TRW Orbital Test Station (DSP)
[illegible]OVS	TIROS Operational Vertical Sound[illegible] (NOAA [illegible])

TRD	Trapped Radiation Detector (Mariner)
TRMM	Tropical Rainfall Measuring Mission (MPE)
TS	Telerobotic Servicer (SSF)
TV	Target Vehicle (Gemini Program)
TW/AA	Tactical Warning/Attack Assessment
TWERLE	Tropical Wind, Energy Conversion and Reference Level Experiment (Nimbus)
UARS	Upper Atmosphere Research Satellite
UVP	Ultraviolet Photometer (Mariner)
UVPI	Ultraviolet Plume Instrument (LACE)
UVS	Ultraviolet Spectrometer (-A, airglow; -O, occulation; Mariner)
VAB	Vertical Assembly Building
VAFB	Vandenberg Air Force Base
VAS	Visible Infrared Spin-Scan Radiometric Atmospheric Sounder (GOES)
VHRR	Very High Resolution Radiometer (NOAA satellite)
VIRR	Visible Infrared Radiometer (Seasat)
VISSR	Visible Infrared Spin Scan Radiometer (SMS, GOES)
VOIR	Venus Orbiting Imaging Radar (Magellan design predecessor)
VRM	Venus Radar Mapper (Magellan design predecessor)
VTPR	Vertical Temperature Profile Radiometer (NOAA satellite)
WBDCS	Wide Band Data Collection System (EOS)
WCRP	World Climate Research Program
WEDO	Worldwide Environmental Disaster Observation Satellite
WEFAX	Weather Facsimile (SMS, GOES)
WF/PC	Wide Field/Plantetary Camera (HST)
WIND II (or 2)	Wind Doppler Imaging Interferometer (UARS)
WOCE	World Ocean Circulation Experiment
WSMR	White Sands Missile Range
WTR	Western Test Range
XIE	X-Ray Imaging Experiment (EOS)
XTE	X-Ray Timing Explorer

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